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THE THORNTON BEACH STATE PARK

DEEP ROTATIONAL LANDSLIDE

DALY CITY, CALIFORNIA

A Thesis Presented

to the Faculty of the Geology Department

San José State University

In Partial Fulfillment of the

Requirements for the Degree

Master of Science

By

Martin D. Liebhardt

May 2002

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APPROVED FOR THE DEPARTMENT OF GEOLOGY

Dr. John W. Williams – San José State University

Paula Messina

Dr. Paula Messina – San José State University

Dr. David Howell – U. S. Geologic Survey

APPROVED FOR THE UNIVERSITY

ABSTRACT

THE THORNTON BEACH STATE PARK
DEEP ROTATIONAL LANDSLIDE
DALY CITY, CALIFORNIA

by Martin D. Liebhardt

Intense winter storms, elevated groundwater levels, and wave erosion from the Pacific Ocean contribute to the slope instability at the Thornton Beach State Park in Daly City, California. The Modified Bishops method under static conditions determined the rotational slumps Factor of Safety to be approximately 1.0. Field observations indicate an imbricate failure plane system that daylights in the Pacific Ocean, creating a geometry that facilitates a cycle of wave erosion and failure. The landslide's time of initiation is dated using a 0.3 meter per year coastal erosion rate and restoring displaced geological units using a computer model. Eroding the shoreline at 100 year intervals, the Factor of Safety is calculated and when it reaches 1.0, the initiation date is determined. Seismic events were not incorporated into the model, and such events might decrease the Factor of Safety. This analysis indicates the Thornton Beach Landslide developed approximately 400 years ago.

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INTRODUCTION

In the winter of 1997 – 1998, major storms hit California causing widespread flooding and landslides. At the end of the winter season over $550 million in property loss and damages had occurred, and 35 counties were declared Federal Disaster Areas (Cannon et al., 1998). During these storms the California coastline was especially susceptible to severe shoreline erosion and landslide damage. This study evaluates a landslide along the coast of Northern California that is susceptible to shoreline erosion and has caused damage to homes, parks, and roads since the area's development.

The study area (Fig. 1) is a landslide in Daly City, California, along the California coast, one kilometer south of San Francisco (Fig. 2). The Thornton Beach landslide area covers approximately 1.5 square kilometers, from Thornton Beach State Park to Fort Funston, which is part of the Golden Gate National Recreation Area. The main focus of this study was the deep rotational landslide in the Thornton Beach State Park (Figs. 3 and 4).

The primary objective was identifying landslide triggering mechanisms, geometry, and kinematics. The research included field work, collecting and analyzing geologic studies, geotechnical reports, aerial photos, and historical and development reports. Using these data, a computer model using the Modified Bishop Method under static conditions of the landslide was produced to determine the stability of the area. This model was used to determine the time of landslide initiation and to predict future instability issues in the area.

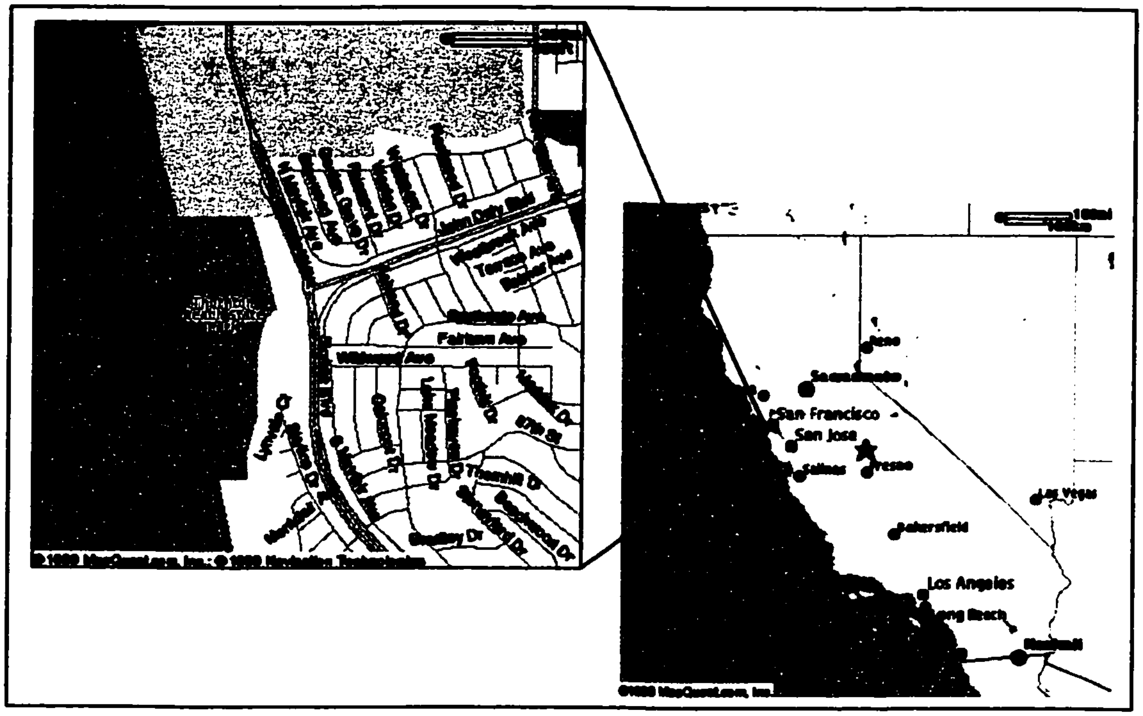


Figure 1. Location of Thornton Beach State Park (Mapquest.com,1999).

Field work began with mapping the geomorphic features and stratigraphy of the Thornton Beach area. With the help of a Global Positioning System (GPS) unit, geomorphic and landslide features were mapped. These features are shown on a three-dimensional, 10-meter Digital Elevation Map (DEM) (Fig. 5).

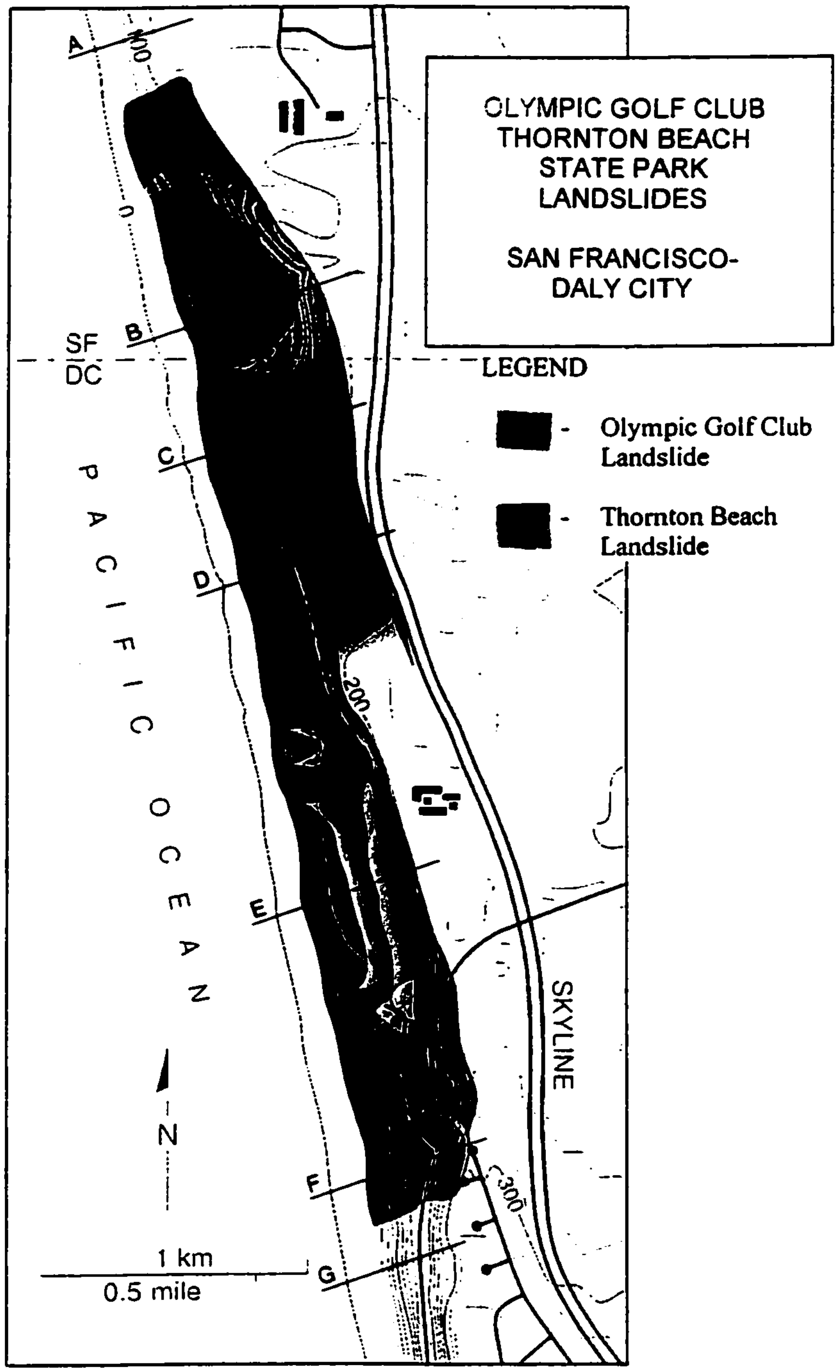


Figure 2. Olympic Golf Course, Thornton Beach State Park Landslide (Lajoie, 1998).

Figure 3. Thornton Beach deep-seated rotational landslide (view to the north).

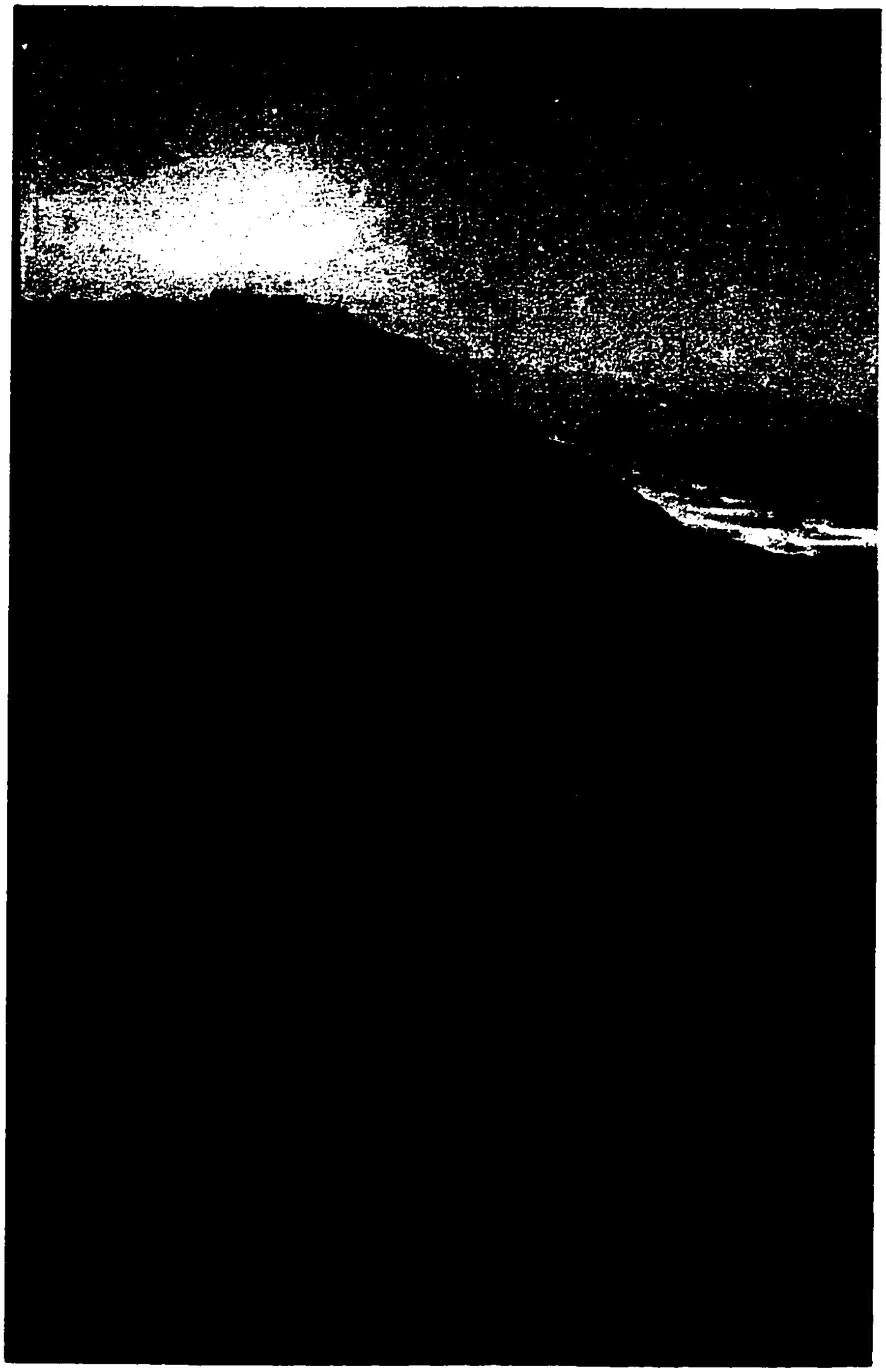


Figure 4. Thornton Beach deep-seated rotational landslide (view to the south).

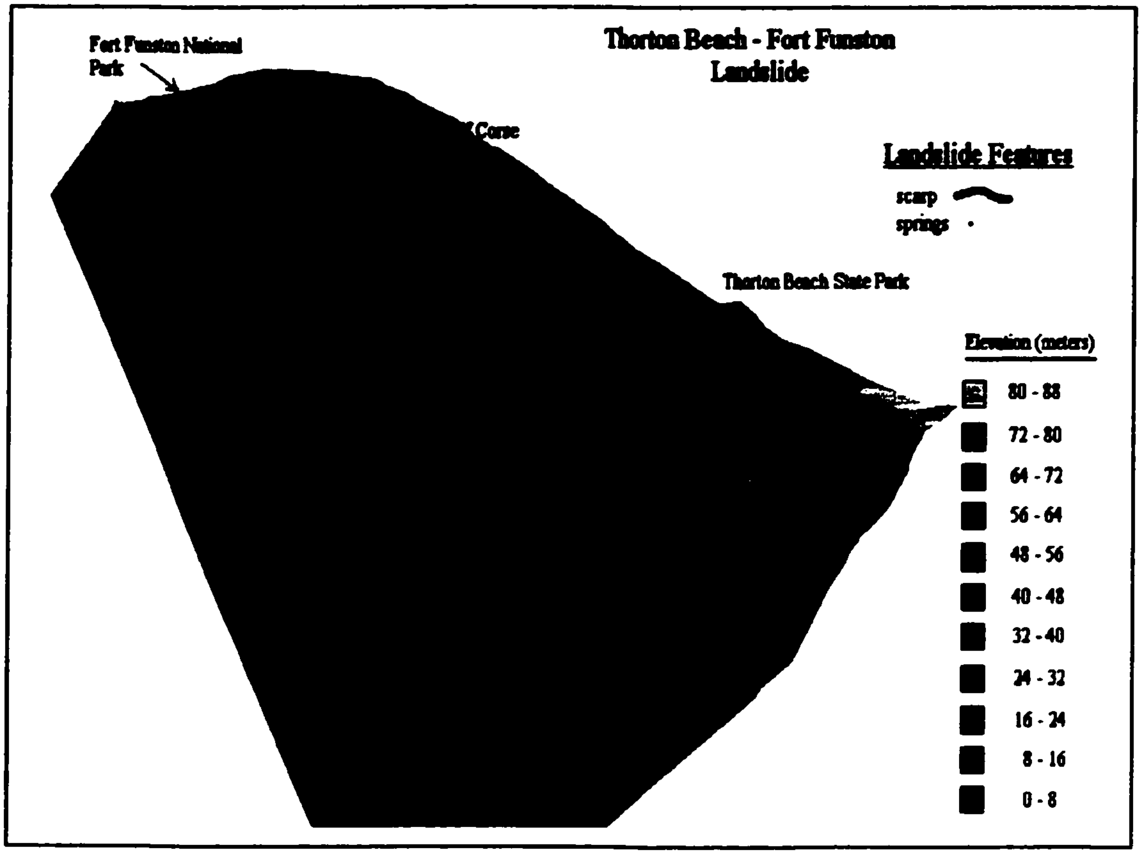


Figure 5. Three dimensional Triangular Irregular Network (TIN) of Thornton Beach – Fort Funston Landslide from the USGS 10 meter digital elevation map.

The sand, silt and clay units of the Merced and Colma Formations are well exposed in the Thornton Beach area. Geotechnical data were collected from development reports and landslide analysis reports conducted in the Thornton Beach area by Caltrans in 1974 and GEI Consultants, Inc. in 1998. The sand, silt and clay units were characterized by correlating them with the geotechnical soil data. Groundwater data were collected from bore holes and wells in the area of the landslide to determine the depth of groundwater. These data were also used to better understand what affects groundwater levels and how groundwater moves in the permeable sand units and the impermeable silt and clay units of the Merced and Colma Formations.

The development of the area and its effects on the stability were analyzed via historical maps and aerial photographs. The landslide was first recorded on an 1852 topographic map. That topographic map (Appendix A) shows a steep scarp and irregular topography along the coast, similar to that of today. Stereoscopic aerial photographs of the areas were purchased from Pacific Aerial in Oakland, California and analyzed to better understand the sequence of changes in surface features and the amounts and types of movement.

Once the data on the geometry, soil properties, and hydrogeology of the landslide were collected, they were used to calculate the Factor of Safety. The computer program, STABL5M, was used to calculate the Factor of Safety. This program allows the user to input geologic cross section, soil properties, and water table levels and calculate the lowest Factor of Safety.

Using the Factor of Safety information and an established erosion rate of 0.3 meters per year along the Pacific Ocean shoreline, an estimated time frame for the initiation of the landslide was produced. Then, using the same method, an anticipated shoreline and corresponding Factor of Safety were created to predict future instability in the area. These methods will be discussed further in the following chapters.

GEOLOGY

Merced and Colma Formations

Thornton Beach State Park is located along the Pacific Ocean where steep sea cliffs expose the Merced and Colma Formations. The geologic map of the San Francisco area (Fig. 6) shows the location of these formations. The Merced Formation is exposed from north of Fort Funston in San Francisco to the south at Mussel Rock in Pacifica. The Colma Formation is a thin coastal deposit that overlies the Merced Formation. Because formations are well exposed, with a wide variety of depositional environments and fossils, they are studied extensively. The purpose of studying the Merced and Colma Formations is to gain an understanding of their impact on slope stability in the Thornton Beach area.

The Merced Formation strikes northwest – southeast for 25 kilometers across the San Francisco Peninsula and is primarily confined to a kilometer-wide structural trough between the San Andreas Fault and the San Bruno Fault (Hunter et al., 1984). To the north of the San Andreas Fault, the Merced Formation overlies the Jurassic and Cretaceous Franciscan Complex as an angular unconformity. The Merced Formation has been dated Pleistocene to Late Pliocene (Clifton and Hunter, 1999). Much of this formation is overlain by the Colma Formation in an angular discordance. Composed of poorly indurated to friable sandstone, siltstone, and claystone, the Merced Formation also

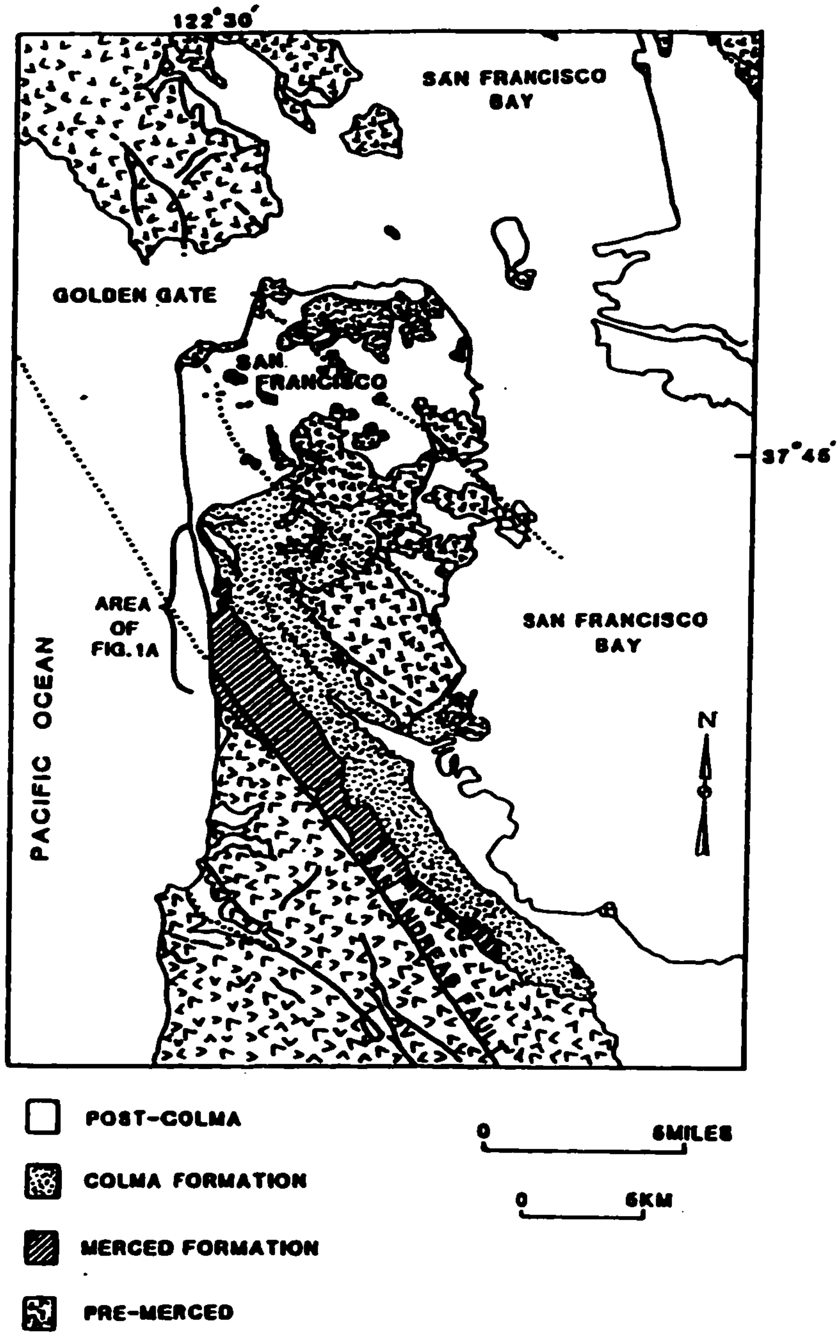


Figure 6. Geologic map of Thornton Beach area showing Merced and Colma Formations (Clifton and Hunter, 1987).

contains conglomerate lenses and volcanic ash. Shallow marine fossils are prevalent in the Merced Formation, which is 1,525 meters thick in the Mussel Rock area (Clifton and Hunter, 1999).

The Colma Formation has been dated based on the last major interglacial stage as having been deposited between 73,000 and 127,000 years ago (Hall, 1965). This formation (Fig. 7) is particularly well exposed at Thornton Beach because of its near-horizontal bedding, in contrast to the Merced Formation, which dips to the northeast. The Colma Formation is a friable-to-loose, fine-to-medium grained arkosic sandstone with minor amounts of gravel, silt, and clay. The estimated maximum thickness is approximately 60 meters (Brabb and Pampeyan, 1983).

Hunter and others (1984) describe nine distinct depositional environments: shelf, nearshore, foreshore, backshore, dune, alluvial, freshwater marsh, swamp or pond, and embayment facies. Each of these facies is repeated throughout the Merced and Colma Formations. The facies represent glacio-eustatic sea level changes, changes in sediment supply and tectonic activity that took place during the Pleistocene and the Pliocene (Hunter et al., 1984; Clifton and Hunter, 1987).

The general trend of the Merced Formation is a northwest strike, almost parallel to the shoreline with a northeastern dip, as shown in Figure 8. In the northern part of the Merced Formation, north of Fort Funston, the beds dip from less than 20° up to 50°. South of Thornton Beach, the dip of the beds steepens to be in excess of 50° to 75°. In the landslide area of Thornton Beach, the dip of the beds is very shallow (0° – 25°) compared to the attitudes to the north and south of the slide. This follows Bonilla's (1960)

Figure 7. Merced and Colma Formations exposed along Thornton Beach head scarp.

observation that "the Merced Formation is apparently unstable in cliff exposures where the dip is low, but stable where the dip is moderate to steep." Figure 9 shows the Thornton Beach area and the stratigraphy of the west-facing slopes as if viewed from a boat traveling along the coast of the Pacific Ocean.

Stratigraphy

The intervals of clay in the Merced Formation (R and Q in Fig. 9) identified by Clifton and Hunter (1987) and Hunter and others (1984), may be responsible for the propensity for landslides in the area and will, therefore, be the main focus of this

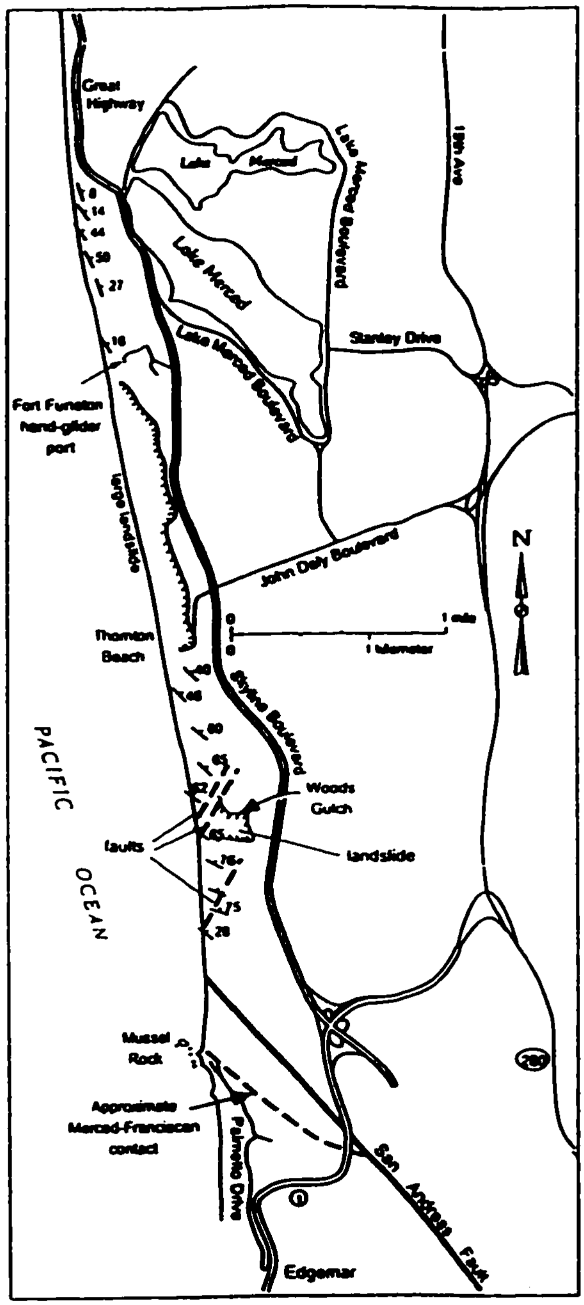


Figure 8. Strikes and dips of the units in the Thornton Beach and surrounding area (Clifton and Hunter, 1987).

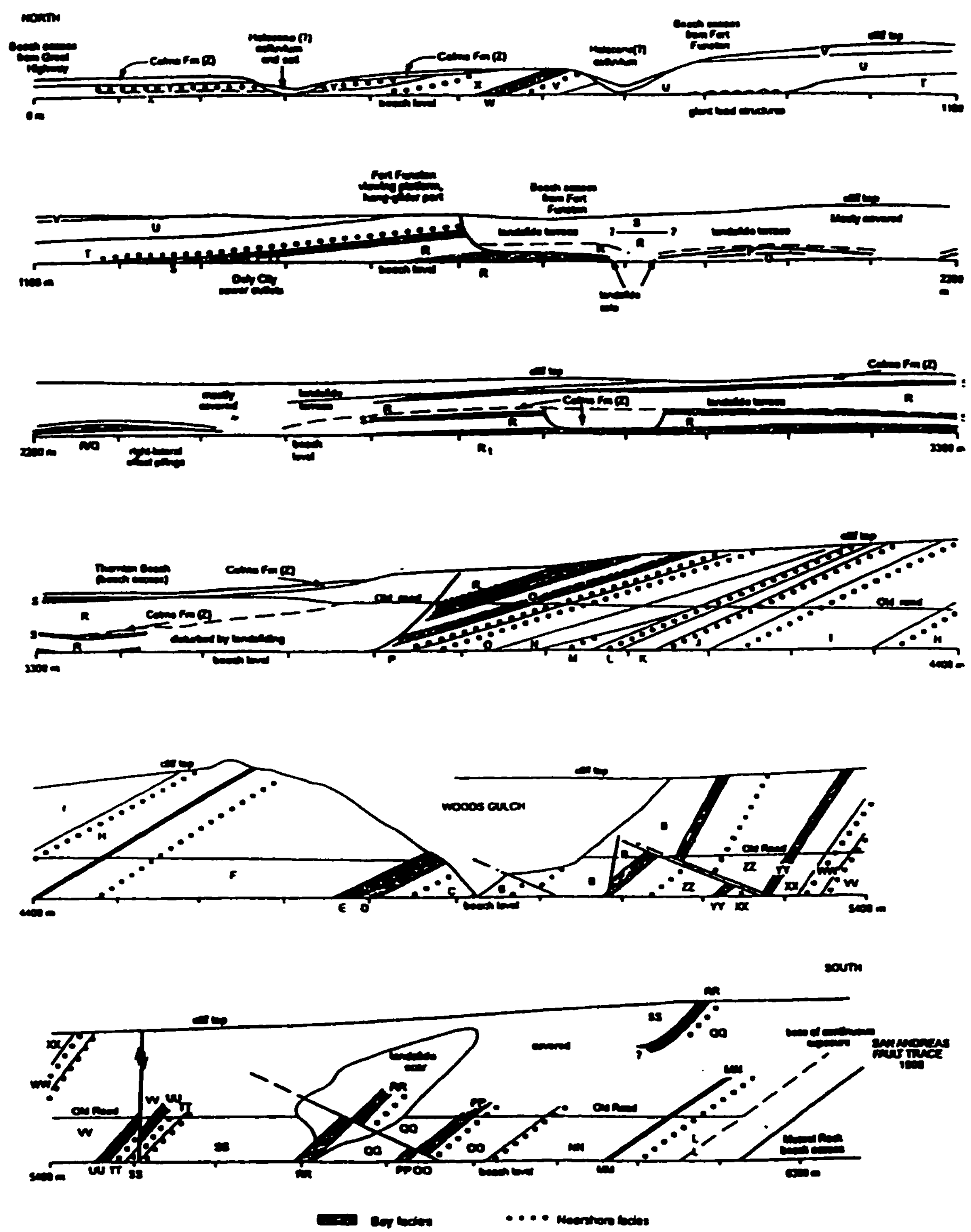


Figure 9. Generalized cross section of Merced and Colma Formations from Mussel Rock to the Fort Funston National Park. Note repeated stratigraphic units (R and S) in the Thornton Beach area. Scale is meters (Clifton and Hunter, 1999).

stratigraphic discussion. Sequence Q is composed of fine interlaminated sand and embayment mud (Unit Q_1) which is 22 meters thick. Unit Q_1 grades upward into Unit Q_2, which is an eolian sand dune approximately 20 meters thick (Unit Q_2). Unit Q_2 also contains clay-rich drapes and layers, as well as vertical tubes lined with clay-rich sand. Sequence R is similar to Q in composition; the basal unit (R_1) is 35 meters thick and composed primarily of embayment mud, overlain by sand dunes 18 meters thick (R_2), paleosols interbedded with backshore and alluvial sand (R_3) 7 meters thick, topped by alluvial sand and gravel with paleosol 2.6 meters thick (R_4) (Hunter et al., 1984).

Figure 9 shows how the stratigraphic units recorded landslide movement. In the area of Thornton Beach State Park, sequences Z (Colma Formation) and S, as well as Unit $R_{4\text{-}2}$, are shown in place along the west facing slope. Below this, along a landslide terrace, the units are also shown in the same sequence located in the head scarp. Correlating the displaced stratigraphic units shows the units have been displaced by as much as 30 meters. Field work conducted verified the displacement of these units.

Faulting and Earthquakes

The San Francisco Peninsula has many active faults as shown on the map in Figure 6. The largest fault is the San Andreas Fault, approximately three kilometers south of Thornton Beach State Park, which cuts through the San Francisco Peninsula. Another fault is the San Bruno which runs north to northwest and is approximately three kilometers north of Thornton Beach. The San Andreas Fault has caused three significant earthquakes in the past century: the 1906 earthquake; the 1957 Daly City earthquake;

and the Loma Prieta Earthquake in 1989. The 1906 and the 1957 earthquakes caused considerable damage to the area around Thornton Beach State Park. The 1906 earthquake had a Magnitude of 8.3 (GEI, 1998) and caused intense shaking and landslides along the sea cliffs. Tension cracks one meter wide were reported along the sea cliffs up to 30 meters inland (Bonilla, 1959). Slope movement was witnessed and reported during this earthquake.

The 1957 Daly City earthquake which had a Magnitude of 5.3 (GEI, 1998) was studied by Bonilla (1959), who reported a number of slides between Mussel Rock and Alemany/John Daly Boulevard. These slides, classified as shallow debris flows or sand runs, were the result of unconsolidated sand close to its angle of repose, which became destabilized by the earthquake. Cracks in pavement and houses in the area also occurred during the 1957 quake.

There was no reported damage to the Thornton Beach area during the 1989 Loma Prieta earthquake, which had a magnitude of 7.1. Although extensive damage occurred in San Francisco, which was farther from the epicenter during the Loma Prieta earthquake, this was probably the result of the large amount and nature of fill in the San Francisco Bay area, fill being subject to greater shaking during earthquakes.

GEOTECHNICAL INVESTIGATION

Geotechnical information is used to understand soil properties and how they affect the stability of the area. The Factor of Safety cannot be determined without specific soil properties, such as total weight, saturated weight, cohesion (c) and the angle of internal friction (phi). This chapter reports on geotechnical investigations conducted in the area of the study, and then presents the soil mechanic properties used to determine the Factor of Safety for the Thornton Beach Landslide.

Soil Tests

Table 1 shows data from geotechnical soil tests conducted on soil from the Westlake area, the development next to Thornton Beach (Bonilla, 1959). The soils are divided into Colma Formation, and Merced Formation, and further subdivided into sand, loam, silt, and/or clay. The values in the table are the averages of numerous soil tests from the Westlake area.

Table 1. Westlake Development soil tests (Bonilla, 1959).

Formation and Material	Moisture Content % of dry wt	Dry Density Kg/m^3	Unconfined Compressive Strength Kg/m^3	Derived Wet Density Kg/m^3	Derived Saturated Density Kg/m^3
Colma Formation					
sand - average	13	1,730	14,096	1,955	1,977
loam - average	17	1,762	10,892	2,062	2,030
Merced Formation					
sand - average	14	1,666	32,132	1,899	1,949
loam - average	30	1,474	104,758	1,916	1,957
clay - average	34	1,410	91,687	1,889	1,944

As recorded in Table 1, there is little difference between the sand and clay units for the wet weights and saturated weights. However, a significant difference exists between the sand and clay units in the cohesion and angle of internal friction values.

Caltrans' geologist conducted a number of soil tests for its study of the Lynvale Court Landslide in 1974. The initial soil test values indicated the Thornton Beach area was stable. Caltrans theorized the failure was progressive and the soil strength was a residual strength rather than the peak shear strength. They tested this theory by shearing undisturbed soil with a direct shear machine. The soil was reconstituted by placing the sheared pieces together under loads simulating original insitu vertical pressures. These direct shear tests were then repeated and the strength of the material, as expected, was much lower than the unsheared material. These results significantly lowered the Factor of Safety. The shear tests were run under dry and wet conditions. The results of the tests are listed in Table 2.

Table 2. Sheared soil tests results and Factor of Safety (Caltrans, 1974)

Soil Type	Cohesion Range (Kg/m^3)	Phi Range (Degrees)	Factor of Safety
Undisturbed Clay	12,200 to 46,360	10 to 0	1.6
Reconstituted Partly Saturated	976 to 4,148	23 to 13	0.7 to 1.4
Reconstituted in the Presence of Water	0 to 2,684	17 to 10	0.6 to 1.0

Bonilla's values for cohesion and phi from his 1960 study of the landslide are shown in Table 3.

Table 3. Soil characteristics used in Bonilla Model (Bonilla, 1960)

Soil Type	Cohesion (Kg/m^3)	Phi (Degrees)
Silt and clay beds	13,908	0

A geotechnical study by GEI Consultants Inc. (GEI) in 1998 was conducted in an area less than 1.5 kilometers south of Thornton Beach at Avalon Canyon. This area is subject to landsliding and the geologic material at the site underlies the Merced Formation. The investigation was conducted to assess the stability of the natural terrain and the engineered slopes. A number of borings were taken during the investigation, and the following tests were performed on the recovered soil samples:

1. Triaxial Shear Tests
2. Direct Shear Tests
3. Grain Size Distribution
4. Moisture Density, and
5. Stability Analysis.

The GEI tests were performed primarily on sand units of the Merced Formation. The results of their tests and data used in their Factor of Safety calculations are shown in Table 4.

Table 4. Soil characteristics used in computer modeling by GEI Consultants

Soil Type	Total Weight (Kg/m^3) (pcf)	Saturated Weight (Kg/m^3) (pcf)	Cohesion (Kg/m^3) (psf)	Phi (Degrees)
Sand	1984 (124)	1984 (124)	0 (0)	30.0
Silty Sand	2080 (130)	2080 (130)	829 (170)	36.0

With information from the prior tests on the different soils in the Merced and Colma Formations, the Factor of Safety can be calculated. The soil was classified as either a sand unit or a clay unit. Then each unit was given soil mechanic properties to determine the Factor of Safety. The values used in the program STABL5M are listed in Table 5.

Table 5. Soil characteristics used in computer modeling for this study

Soil Type	Total Weight (Kg/m^3) (pcf)	Saturated Weight (Kg/m^3) (pcf)	Cohesion (Kg/m^3) (psf)	Phi (Degrees)
Sand	1890 (118.5)	1938 (121.4)	0 (0)	32.0
Clay	1890 (118.0)	1938 (121.0)	1098 (225.0)	0

HYDROLOGIC FACTORS

Water is generally considered the primary triggering element of slope instability. Sullivan (1975) identified seven factors that affect slope stability in the Thornton Beach area. The seven factors are: 1) steep cliffs, 2) wave erosion, 3) the unconsolidated nature of the sands, 4) steep dips of the Merced Formation, 5) intense winter rainfalls, 6) urban development that affects drainage, and 7) seismic activity. Of the seven factors mentioned, three involve water processes - wave erosion, rainfall, and drainage. This chapter will focus on the hydrologic factors of the landslide, the effects of heavy rainfall on groundwater levels, and the impact of wave erosion on the stability of the area.

Groundwater

Bonilla (1957) and Sullivan (1975) note the relative impermeability of the silt and clay units and the relative high permeability of sand units of the Merced Formation. Both authors mention that groundwater tends to travel at the contacts between the sand and clay units (Fig. 10). These contacts are marked by springs and seepages visible year round. Springs were noted in the field and were mapped using GPS, as shown in Figure 5. Some springs are as much as 30 meters above sea level.

A study of the Westside Basin groundwater levels was conducted by Bookman – Edmonston Engineering, Inc. (1996) and includes a groundwater contour map of San Francisco as shown in Appendix B. This map shows the groundwater levels for a deep aquifer in the area. In the area of Thornton Beach State Park, the water levels are

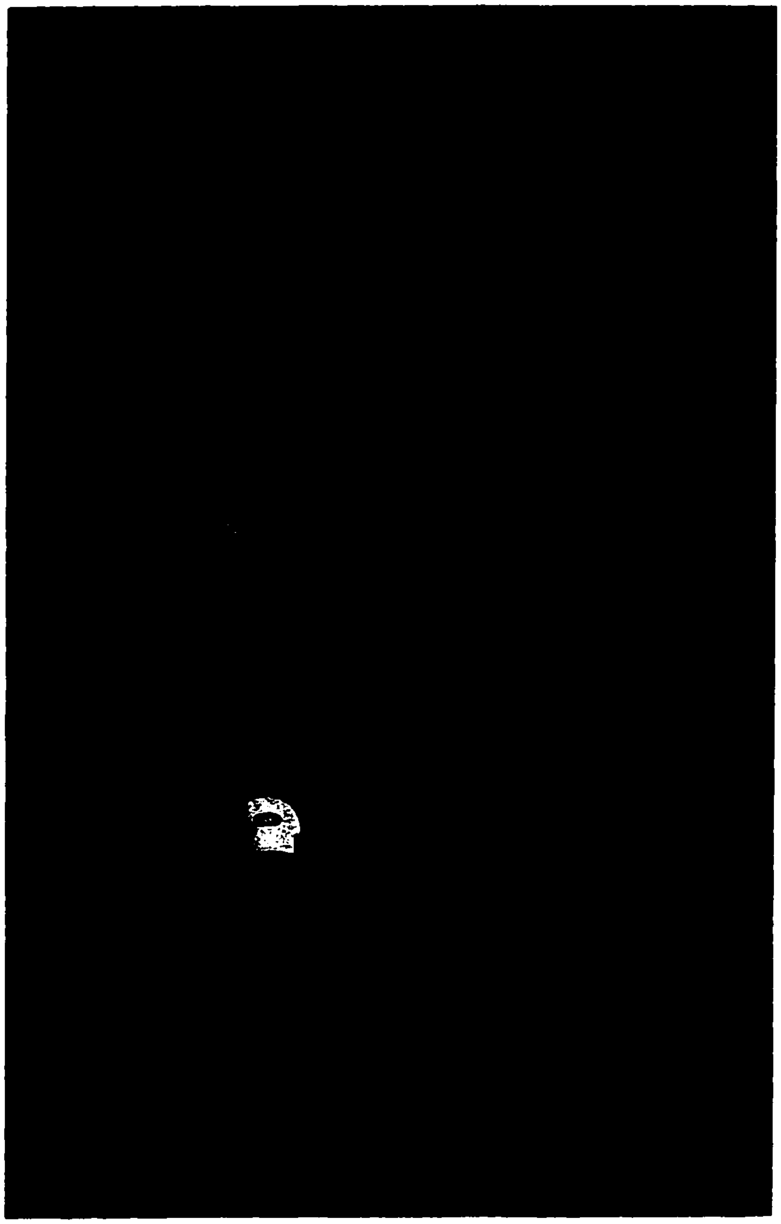


Figure 10. Spring seeping between clay and sand units near Thornton Beach State Park. Baseball cap included for scale.

estimated to be at zero mean sea level (msl) (Bookman –Edmonston, 1996). However, because of the alternating layers of permeable sand, impermeable clay and silt, water levels are quite variable and perched water tables are common in the area.

Bore Holes

Caltrans drilled three borings as shown on the map and the cross-sectional view in Appendix C. Each bore hole log reveals the soil type based on the Unified Soil Classification System and a brief description of the soils such as slicks, fractures, and color. Water table elevations and landslide movement are also included in the bore logs. The holes were drilled between June 15, 1972 and July 17, 1972. As shown in the map (sheet 3 of 6), D-1 and D-2 drilling holes were located along the abandoned highway below the Lynvale Court cul-de-sac, and D-3 was drilled at the top of the bluff at the end of Lynvale Court. During the Caltrans drilling operation, water levels were measured and the results are listed in Table 6. As shown in the table, water table levels ranged from 7.0 meters below grade surface (bgs) in bore hole D-2 to 46.9 meters bgs in bore hole D-3. D-1 and D-2 were located approximately 120 to 140 meters from the Pacific Ocean shoreline. Although the Bookman – Edmonston (1996) study shows the water table elevation at 0 meters msl, the Caltrans' borings show the water table exists, at least locally, as high as 54 meters above msl in the area.

Table 6. Caltrans drilling water table elevations for the Lynvale Court Landslide (all measurements are in meters)

D-1

Date	Depth To Water	Elevation of Well Casing	Groundwater Elevation
Jul-73	20.7	61.0	40.3
02-May-74	22.8	61.0	38.2

D-2

Date	Depth To Water	Elevation of Well Casing	Groundwater Elevation
Jul-73	7.0	61.0	54.0
02-May-74	11.3	61.0	49.7

D-3

Date	Depth To Water	Elevation of Well Casing	Groundwater Elevation
Jul-73	46.9	94.5	47.6
02-May-74	46.3	94.5	48.2

Rain Storms

The winter of the 1997 – 1998 El Niño caused $550 million worth of damage across California from landslides and flooding (Cannon et al., 1998). Intense rainy winters affect slope stability. The past 40 years of rainfall data showed that higher than normal rainfall generally decreased slope stability. Appendix D shows the monthly rainfall for San Francisco for the past 40 years (NOAA, 1999). The average annual rainfall over the past 40 years is approximately 54.9 centimeters (21.6 inches). Winters with at least one and a half times the average rainfall, or 82.3 centimeters per year (32.4 inches), have been put in bold face type in Appendix D to indicate heavier rainfall and associated increased potential for landslides. This is especially evident during 1982-1983, 1983-1984 and 1997-1998 (El Niño) and rainy seasons, when extensive storms caused numerous landslides and debris flows. During the El Niño winter, the Olympic Golf Course west of Highway 35 was damaged by landslides and as a result most of the golf course on the west side of the highway is no longer in use.

Wave Action

The geologic – topographic history of the San Mateo and San Francisco counties' coastlines dates back at least 15,000 years. During the Wisconsin glacial period, sea level was approximately 120 meters lower than present. The sea level began to rise around 14,000 years ago and at 7,000 to 5,000 years, the sea level rose to its current height. Therefore, approximately 5,000 years ago, the erosion and modification of the San Mateo/San Francisco coastline began and has continued to this day (Tinsley, 1972).

The area from Thornton Beach State Park to Fort Funston is subject to coastal erosion due to the action of ocean waves. Coastal retreat in San Mateo County has been studied by Tinsley (1972), who estimated the average rate of coastal erosion to be approximately one-third meter (or one foot) per year based on shoreline maps, aerial photos and maps dating back to 1850, as well as on his own surveying and measuring of subdivision lines and natural markers along the coast.

Tinsley (1972) describes the Thornton Beach area as "unbenched sea cliffs composed of poorly consolidated, friable material" with sea cliffs rising from msl, at or close to the angle of repose. Major landslides and slumps are apparent, such as Tinsley noted (1972) when he described wave action continually eroding the base of cliffs, resulting in debris flows and landslides.

Waves erode the slopes at their bases making them unstable and prone to sliding and slumping. Ranger Steve Prokop (1999) at Fort Funston reported that the cliffs there have eroded 6 meters in the past two years (1997 – 1999). This may be an exceptionally high rate due to a combination of two higher than average rainy years (1997 – 1998 and 1998 – 1999) causing instability in the slopes, along with the continuous wave erosion.

Figure 11 shows coastal retreat in Pacifica, located 1.8 kilometers south of Thornton Beach State Park. In this photo, the red lines indicate the shoreline and the corresponding year. This photo illustrates the amount of coastal retreat, which is similar to that at Thornton Beach.

Figure 11. Coastal retreat in Pacifica, California.

HISTORY AND DEVELOPMENT

Urban development of the Thornton Beach area began in 1874 with a carriage and wagon tunnel through Mussel Rock which is composed of greenstone of the Franciscan Complex in Pacifica. The tunnel was part of the beach route between San Francisco and Pacifica (Sullivan, 1975). By 1905, the Ocean Shore Railroad was under construction. The railroad was built along the Thornton Beach cliffs (Caltrans, 1974) on a cut bench, 45 - 60 meters above sea level. This was the same path later used for State Highway 1, known as the Pacific Coast Highway.

The railroad was still under construction when the 1906 San Francisco earthquake occurred, and numerous landslides along the coast damaged the railroad line. However, work continued on the railroad and in October 1907, the first passenger train traveled from San Francisco to Pacifica (Sullivan, 1975). The railroad abandoned the section from Pacific Manor to Thornton Beach a short time later because of landsliding (Caltrans, 1974).

By 1935, the State had regraded and widened the old railroad line for two-lane Route 56 (Highway 1). The highway ran along the coast from San Francisco to Santa Cruz. Like the railroad line, the highway was very difficult to maintain because of landsliding. In 1953, the highway was re-routed away from the landslide-prone coast to more stable ground inland. Severe damage from the March 22, 1957 earthquake and major storms eventually closed Highway 1 in this area in 1958 (Sullivan, 1975 and Bonilla, 1960) (Figs. 12 and 13).

Figure 12. Landslide destruction of Highway 1 at Thornton Beach in 1963 (Sullivan, 1975).

Much of the housing development in the area took place in the 1950's and 1960's. The construction of homes dramatically changed the landscape of the area. This is especially evident approximately 3 kilometers south of Thornton Beach near Mussel Rock, where entire hill tops were leveled and canyons filled for housing projects. Development in the Thornton Beach area, known as the Westlake Palisades subdivision, was started in 1954 and completed in 1958 (Caltrans, 1974).

Figure 13. Landslide destruction of Highway 1 at Thornton Beach in 1963 (Sullivan, 1975).

Aerial Photographs

A collection of eight sets of photographs from 1935 - 1997 of the Thornton Beach area was obtained. For each set of photographs, a description of the movement, geomorphic features, vegetation, and landmark changes was made. However, only photographs with major changes are shown as figures.

The aerial photographs of the Thornton Beach area suggest slope instability was occurring in 1935, at the time of the first aerial photograph. This is especially true along the beach where steep cliffs show landslide scarps and irregular topography. The following sections describe each of the aerial photographs collected. A discussion of area development and landslide geomorphic features follows.

1935

- The 1935 photograph (shown in Fig. 14) shows agricultural fields and very little development, with the exception of the Olympic Golf Course located east of the Thornton Beach area.
- Landslides and debris flows are noticeable above and below Highway 1 along the steep cliffs.
- Disrupted topography and steep cliffs are located along the shoreline in the Thornton beach area.
- A scarp and disrupted topography is visible near Highway 35 and the Olympic Golf Course.

1958

- The 1958 photograph shows housing (Westlake Palisades) developments under construction in the Thornton Beach area. Houses along Skyline Drive are completed, and the Lynvale Court houses are under construction.
- Highway 1 is severely damaged and is closed.
- Dislocated blocks of highway asphalt are prevalent downslope of Highway 1, and toe debris covers much of the upslope side of the highway.
- Alemany/John Daly Boulevard has small debris flows along its western slope.
- Much of the slope of the Thornton Beach Landslide is overgrown, and the basin below the slope is covered with brush and materials from the debris flows.

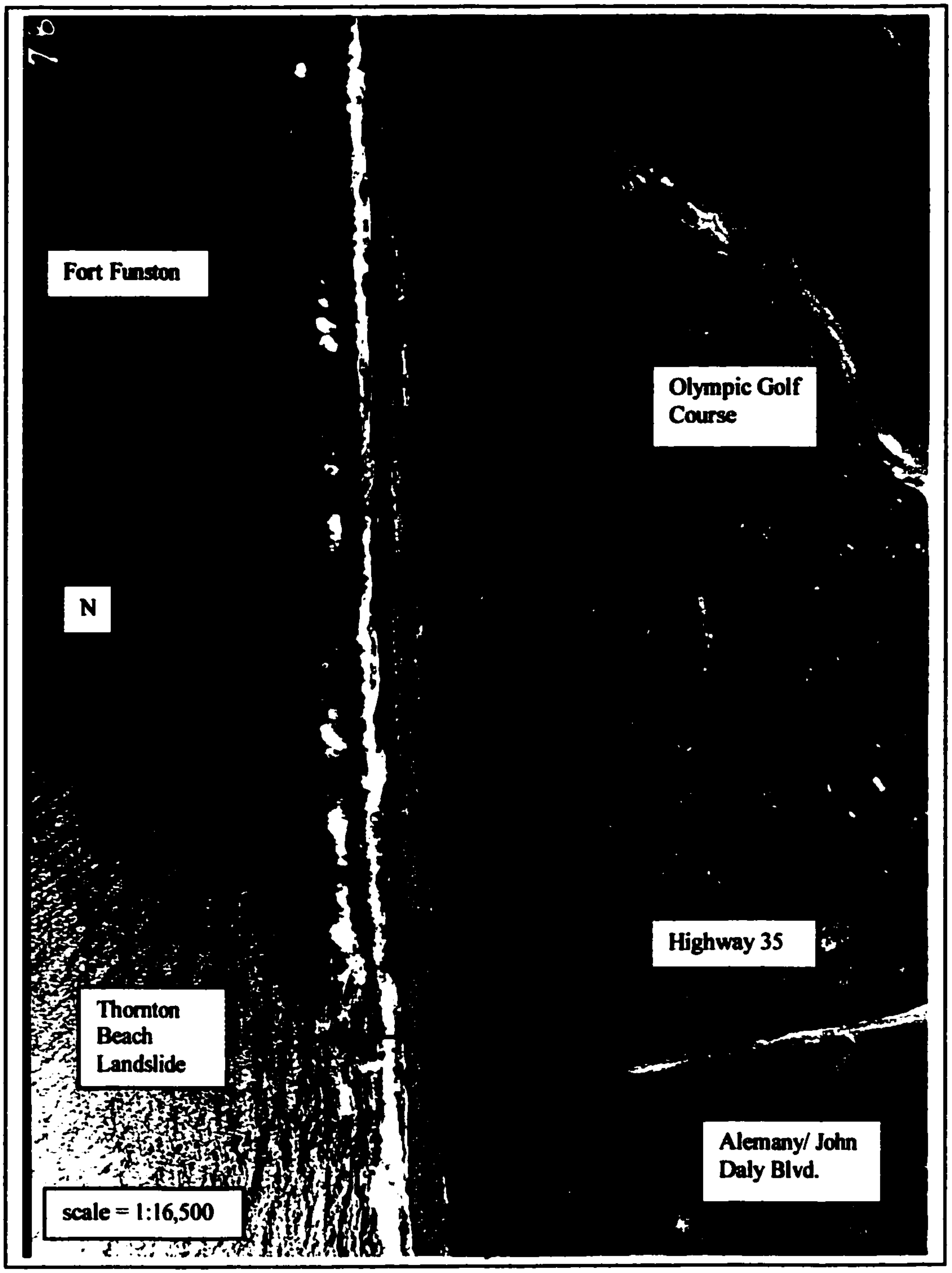


Figure 14. 1935 aerial photograph of Thornton Beach area.

1969

- Lynvale Court and Skyline Drive are unaltered and all the houses are intact.
- A parking lot for Thornton Beach park that is accessed by Alemany/John Daly Boulevard is in place.
- Highway 1 is broken up and separated from Alemany/John Daly Boulevard just below the north end of Skyline Drive and Lynvale Court. The damaged highway area is in the path of the Lynvale Court Landslide.
- Below the Lynvale Court cul-de-sac the slope is stable and overgrown, but farther downslope much of the old highway is gone.
- Alemany/John Daly Boulevard is intact, but there are drainage gullies and debris flows along the slope into the parking lot. The slope near the stables also has a few debris flow scars and drainage gullies.

1975

- The Lynvale Court Landslide (shown in Fig. 15) failed and the six houses in the area are no longer present. The cul-de-sac asphalt is cracked and the failure extends from the street to the beach, approximately 60 meters in length.
- Alemany/John Daly Boulevard and the Thornton Beach parking lot, just to the north of the slide, both appear to be intact, but the parking lot has sediment along the edges from debris flows.
- As in the earlier pictures, the beaches display steep cliff faces (approximately 30° – 35°) with little vegetation due to the continuous wave action eroding the landslide toe.

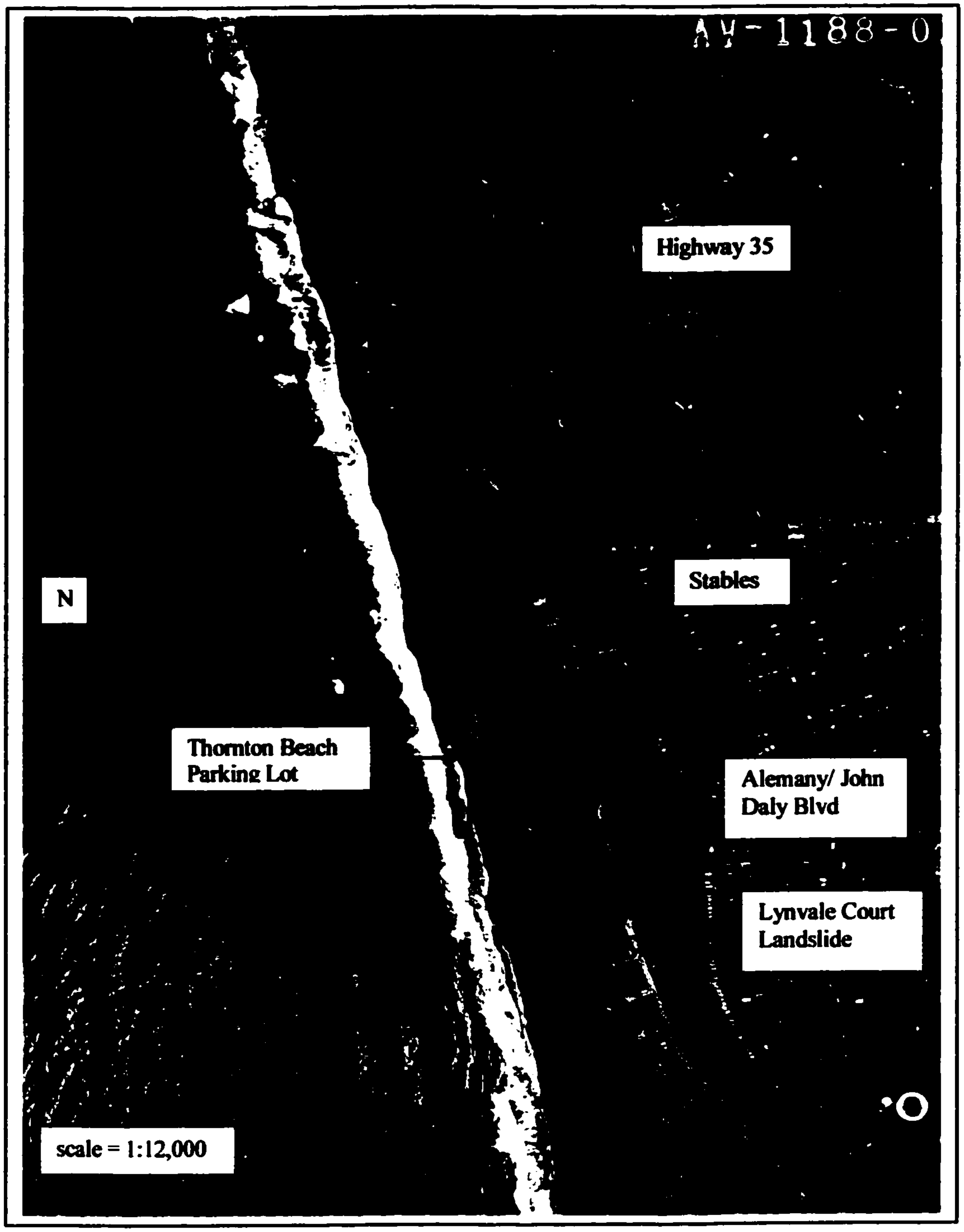


Figure 15. 1975 aerial photograph of Thornton Beach area.

1983

- Thornton Beach parking lot is no longer in use (shown in Fig. 16) and is completely covered with slope material. The slope material wash is attributed to the heavy rains during the winters of 1981-1982 (96 centimeters) and 1982-1983 (96 centimeters).
- Alemany/John Daly Boulevard is damaged from a large failure on the eastern side of the hairpin turn and the road is completely separated at the northern end of the Lynvale Court Landslide.
- The Lynvale Court Landslide, which had previously cracked but had not disconnected from the road, is now completely separated from the road.
- Along the cul-de-sac there are overturned trees, irregular topography, and drain pipes along the landslide path which reach the beach.
- The old Highway 1 route is overgrown and covered by landslide deposits.
- To the northeast, landslide damaged Highway 35 has been repaired with new asphalt.
- Scarps and landslide damage can be seen along Highway 35.
- The photograph shows the Olympic Golf Course has been expanded across Highway 35, approximately 300 meters from the shoreline.

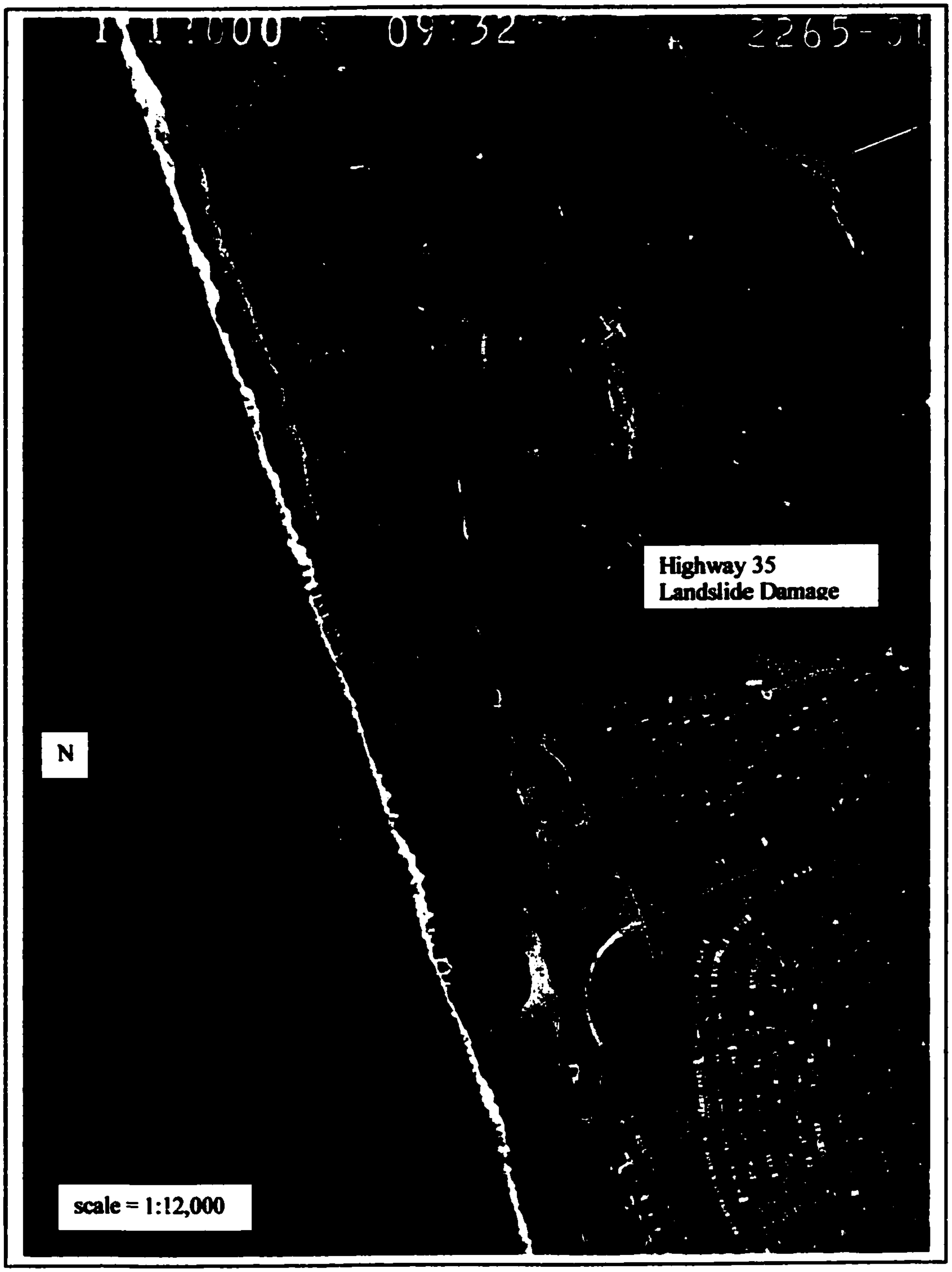


Figure 16. 1983 aerial photograph of Thornton Beach area.

1991

- A ruptured drainage pipe is at the bend of Alemany/John Daly Boulevard and the road is closed.
- Damage to Highway 35 seen in the 1983 photograph has been moved farther to the east.
- The land surrounding Highway 35 is disrupted and scarps can be seen next to the road.

1995

- This photograph show little change from the 1991 photograph except for the increased degradation of Alemany/John Daly Boulevard.
- Alemany/John Daly Boulevard has broken and cracked pavement.
- The slopes to the north are overgrown with vegetation.
- The landslide-generated basin below is overgrown as well, with the exception of the areas where the sediments from the Alemany/John Daly Boulevard drainage pipe rupture have deposited alluvium.

1997

- Much of Alemany/John Daly Boulevard is disrupted with debris flows and failures along its slopes (shown in Figure 17).
- The Lynvale Court Landslide is covered with vegetation except at the bottom of the slide near the beach.
- The Thornton Beach Landslide has shallow debris flows along the slope, and the basin below is overgrown with vegetation.

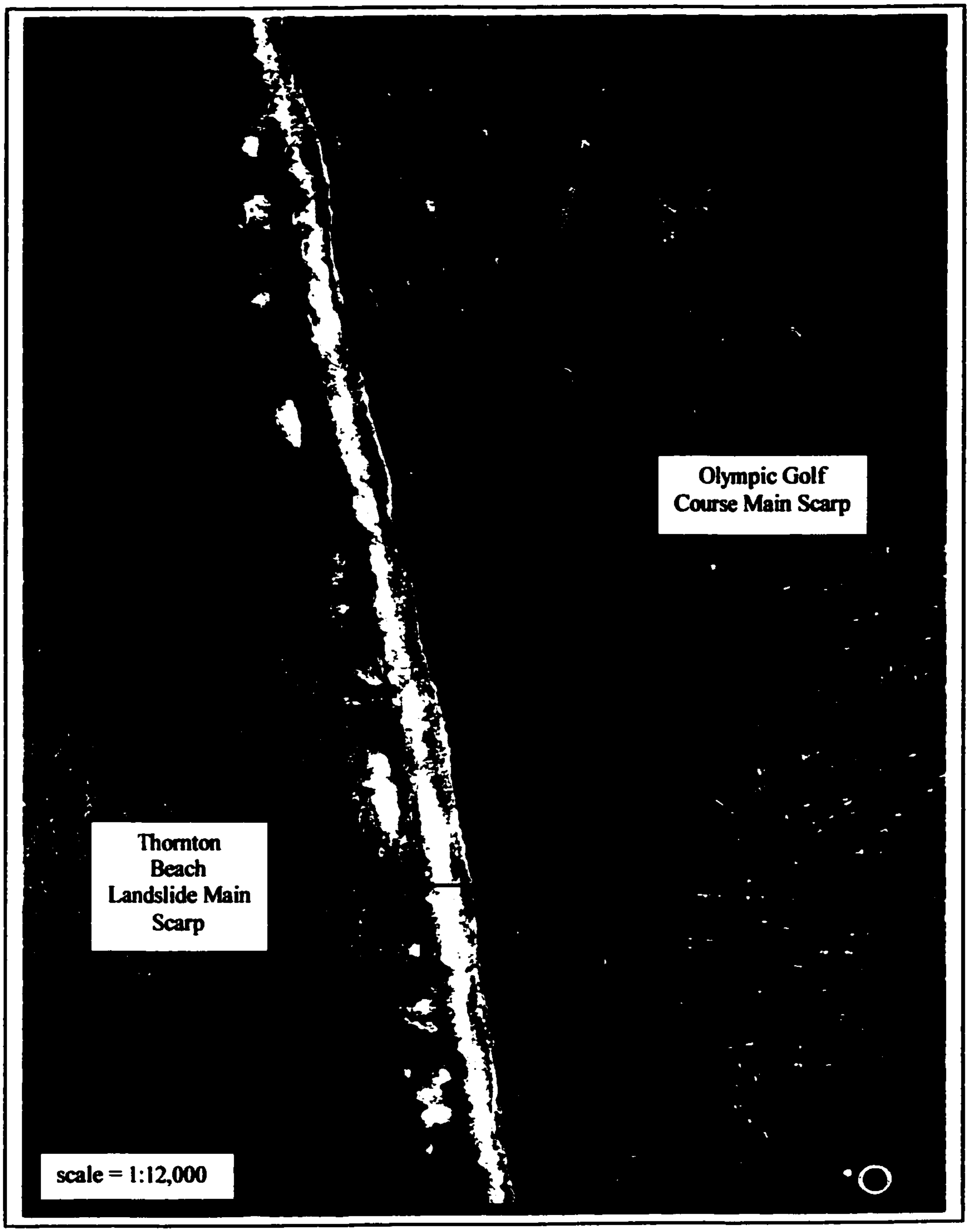


Figure 17. 1997 aerial photograph of Thornton Beach area.

By 1997, the shoreline is much more disrupted and irregular than in 1935. The slopes shown in the 1997 photograph are barren of vegetation and the scarps and debris flows are more prevalent than in the 1935 photograph.

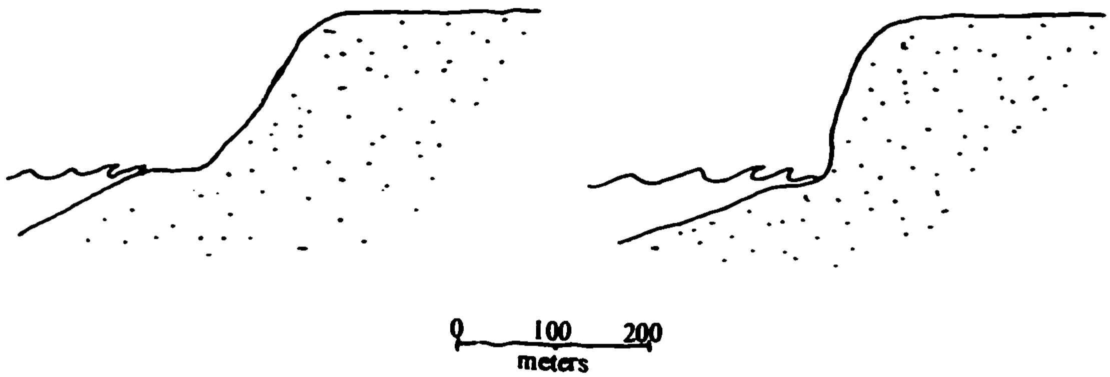
LANDSLIDE CHARACTERISTICS AND MODELING

A model of the landslide was created based on geologic, geotechnical and hydrologic information. The model was developed to determine the Factor of Safety, the approximate time the failure occurred, and the extent and location of future damage.

Field Observations

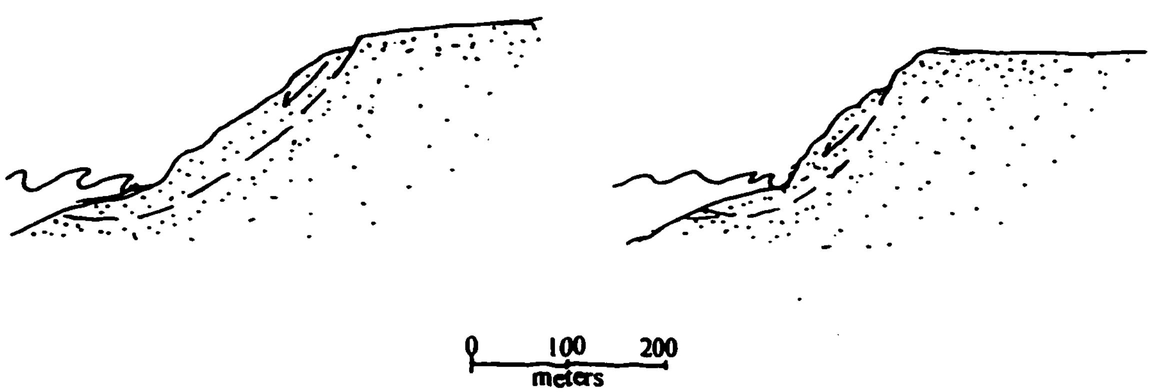
As the Thornton Beach Landslide continues to be eroded by wave action, the land to the east becomes unstable and prone to landsliding. The landslides are more likely to fail along a plane that is already established by previous landslides, because the material in the slip plane will be at residual strength rather than peak strength. This creates an imbricate slip system of landslides in the Thornton Beach area.

Figures 18 A - F are a series of sketches of the Thornton Beach area illustrating the hypothesis that an imbricate slip plane system developed due to wave erosion and progressive slope failures. The first sketch (Fig. 18-A) represents how the Thornton Beach area may have looked prior to the landslide. The relatively steep slopes, close to the angle of repose of the slope forming materials (approximately 32°), were undermined and eroded by constant wave action shown in Figure 18-B, eventually leading to the landslide (Figure 18-C). Figure 18-D shows the wave action continuing to erode the shoreline and transporting the landslide debris down the coastline by longshore currents. Because of the continual wave action, the landslide never stabilizes, and continues to slip. As the landslide debris and the shoreline are eroded, the area farther inland becomes less stable, leading to another landslide (Fig. 18-E). The second landslide slip plane joins the original landslide slip plane because the soil is at residual strength instead of peak strength, creating an imbricate system of landslides (Fig. 18-F). This cycle of erosion and failure led to the series of landslides in the Thornton Beach area.



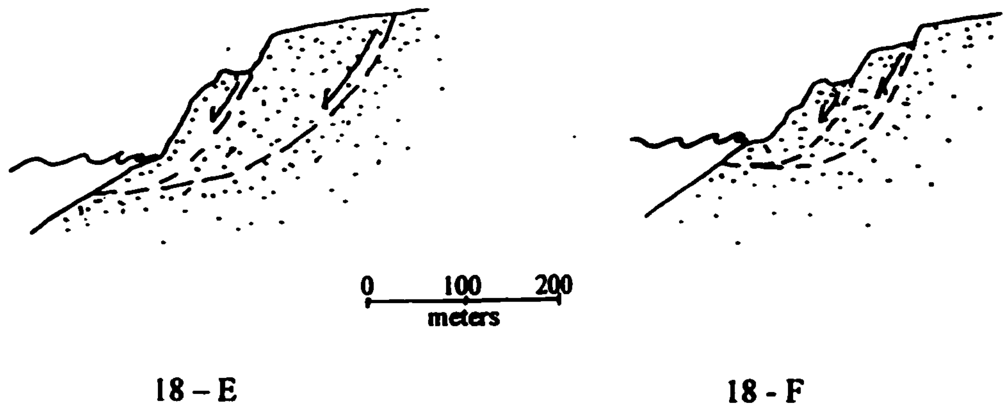
18 – A 18 – B

Figures 18 A – B. Sketches of the Thornton Beach area showing cycle of wave erosion and undercutting.



18 – C 18 - D

Figures 18 C – D. Sketches of the Thornton Beach area showing the initiation of the landslide and the erosion of the landslide debris.



Figures 18 E – F. Sketches of the Thornton Beach landslide showing cycle of wave erosion, undercutting and failure that lead to the imbricate system landslides.

Modeling

To test the imbricate slip plane hypothesis and to determine the Factor of Safety for the Thornton Beach Landslide, a geologic cross section of the deep rotational landslide was constructed. The geologic cross section (Appendix E) illustrates the different stratigraphic units and the corresponding sand and clay units associated with the Colma and Merced Formations. The Modified Bishop method of slope stability for circular failure was used under static conditions. Because the Colma and Merced Formations are composed primarily of sand and clay units, two soil types were entered into the program: one for sand and one for clay (Table 5).

Factor of Safety

The soil parameters, water table, and a cross section of the landslide were entered into the STABL5M program. High (7 meters below surface) and low (20 meters below surface) water table conditions were considered and the Factors of Safety were calculated. STABL5M allows the user to fix the location of the slip plane's beginning and end. Factors of Safety were calculated for slip planes close to the Thornton Beach Landslide scarp approximately 180 meters from the Pacific Ocean, and then calculated for slip planes that could start between 180 meters to 360 meters from the Pacific Ocean. The ten lowest Factors of Safety from 400 potential slip planes were then calculated.

The computer modeling results show the area to be unstable, especially when the groundwater level is 7 meters below the ground surface and the slip plane starts approximately 300 meters east of the Pacific Ocean. The results of the various runs showing the ten lowest factors of safety are in Table 7, and outputs are in Appendix F.

Table 7. Factors of Safety for Thornton Beach area with approximate location of slip plane initiation and water table level

Distance from the Pacific Ocean (meters)	Water table Level below Ground Surface (meters)	Lowest Factor of Safety	Highest Factor of Safety
180	20	1.29	1.52
180	7	1.04	1.21
300	20	1.12	1.34
300	7	0.89	1.02

The data in Table 7 support the imbricate slip plane hypothesis suggesting that the Thornton Beach Landslide slip surface has an additional slip plane farther inland, making the area to the east of the landslide unstable. The lowest Factors of Safety occur when the water table is high and the slip surface is initiated approximately 300 meters from the shoreline. This distance correlates to the same location where the damage would occur if the Olympic Golf Course Head scarp continues to develop in its present southwardly direction. Therefore, the computer model agrees with what is seen in the field regarding slip plane locations and the imbricate slip system with multiple landslides.

Photographs from July, 1998 (Figs. 19 – 21) display the damage from the active landslide and the damage to the golf course and Route 35. The initiation point of the Olympic Golf Course landslide is at the same location as the initiation point modeled by STABL5M. The landslide damage could be seen in the 1983 aerial photograph, and it probably resulted from the heavy winter rain storms of 1981 – 1982 and 1982 – 1983. Further damage takes place during the last El Niño winter (1997 – 1998) which caused severe damage on the golf course and additional movement along the head scarp.

The output suggests the rotational slip plane ends west of the shoreline of the Pacific Ocean. Field observations by Baker (2000) mention that the landslide can be seen moving during low tide. In 1983 while assessing the damage to the Olympic Golf Course James Baker, The Santa Clara County Geologist, took photographs while

Figure 19. Aerial photograph showing landslide damage to golf course (July 1998).

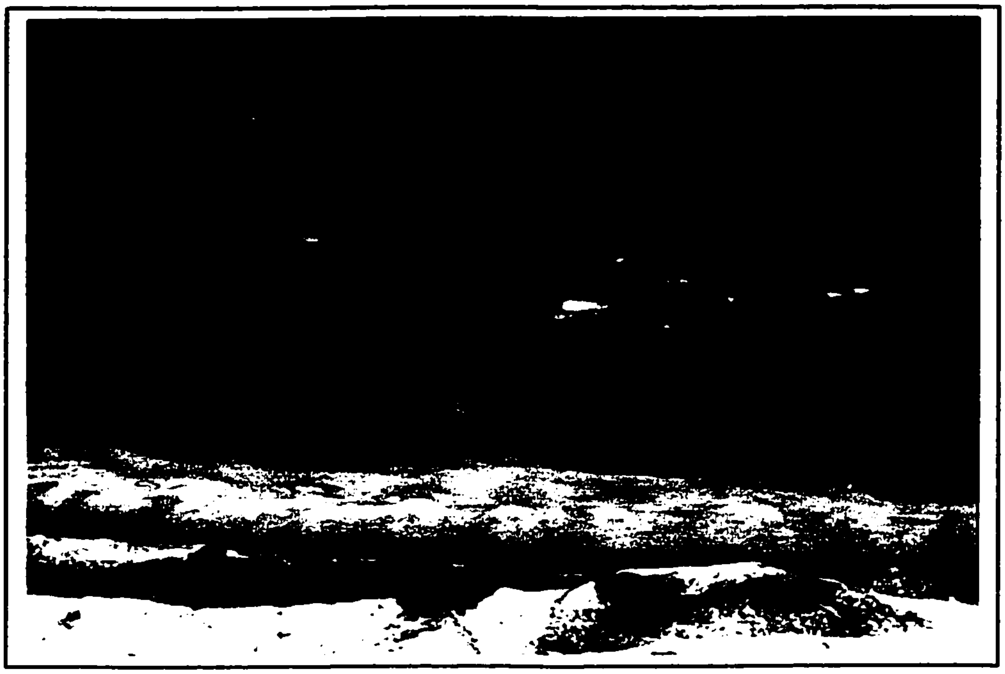


Figure 20. Aerial photograph showing landslide damage to golf course (July 1998).

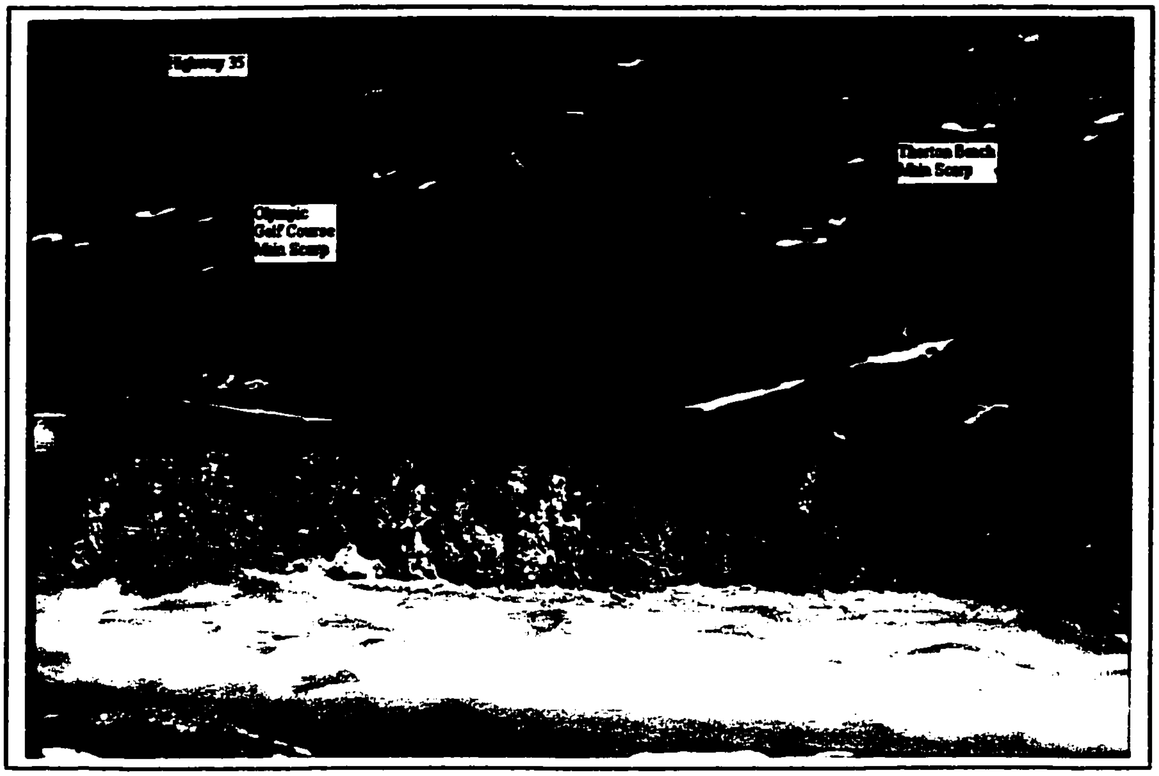


Figure 21. Aerial photograph showing locations of Olympic scarp and Thornton Beach scarp (July 1998).

walking along the beach below the golf course. The photographs (Figs. 22 – 24) show an actively creeping slide mass (some 30 meters thick) emerging through the wet sand during low tide. According to Baker, the thrusts had "several inches of vertical and horizontal displacement" before breaking down (Baker, 2000).

Predictive Tools

Inferring that sea level reached its maximum, post glacial position 5,000 years ago, and using the erosion rate of 0.3 meters per year, calculations indicate the shoreline would have been 1.8 kilometers west of its current location. Using the computer model and these rates a scenario can be produced to determine when the Thornton Beach landslide took place.

The 1853 topographic map (Appendix A) shows landslide topography similar to that of today, confirming the presence of a landslide at least 150 years ago. Since there are approximately 0.3 meters of wave erosion per year in the Thornton Beach State Park area, and this type and rate of erosion has occurred for the past 5,000 years, this information can be used to predict future instability problems in the area. By using the erosion rate of the shoreline and the Factor of Safety, an estimate of the landslide's age may be produced.

Dating the Landslide

Models representing the Thornton Beach Landslide as it may have appeared in the past were created. The models represented different stages of the landslide development, and geologic units that are currently displaced or eroded were restored to represent

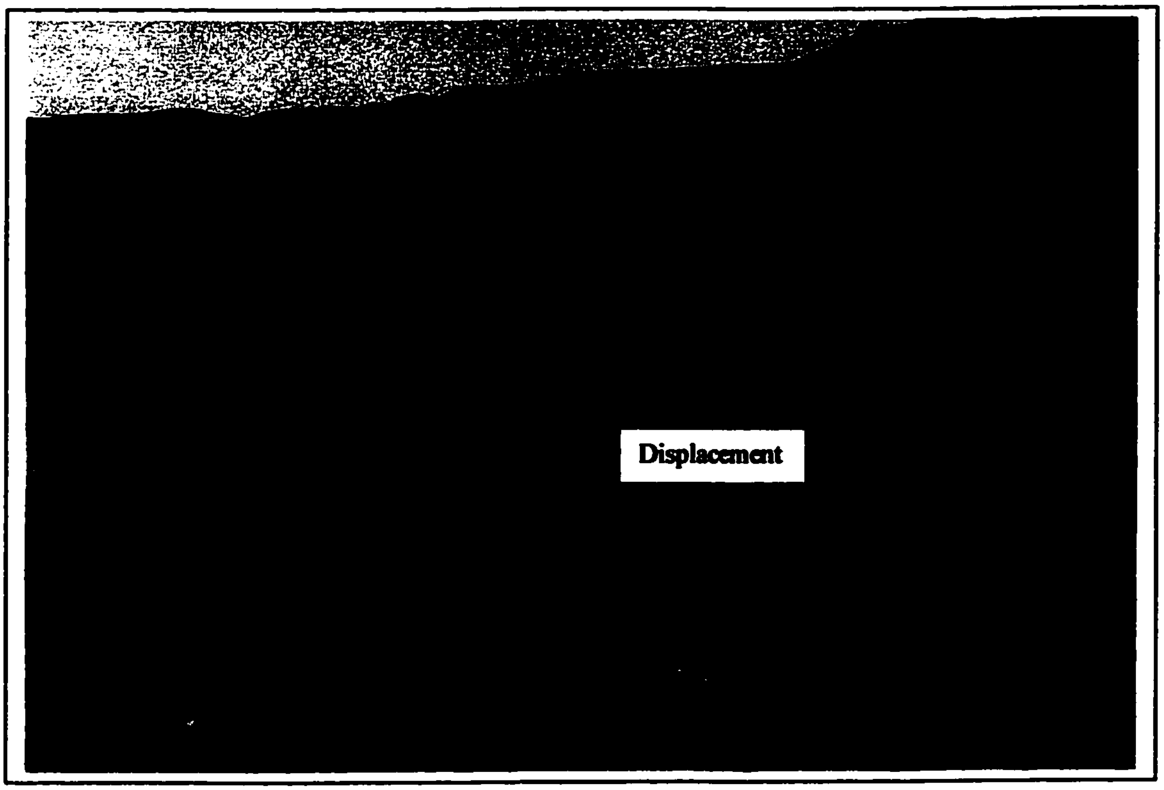


Figure 22. Photograph showing active creeping of the Thornton Beach Landslide. Fractures are approximately 1 to 5 centimeters apart (J. Baker).

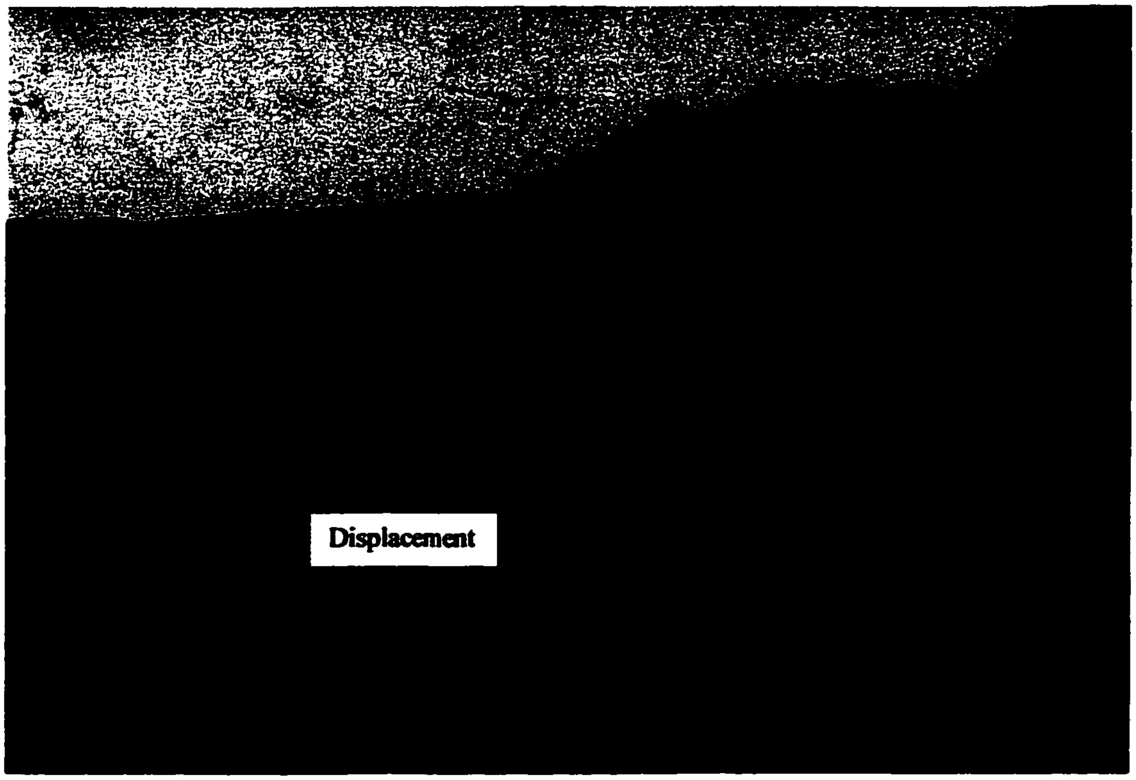


Figure 23. Photograph showing active creeping of the Thornton Beach Landslide. Fractures are approximately 1 to 5 centimeters apart (J. Baker).

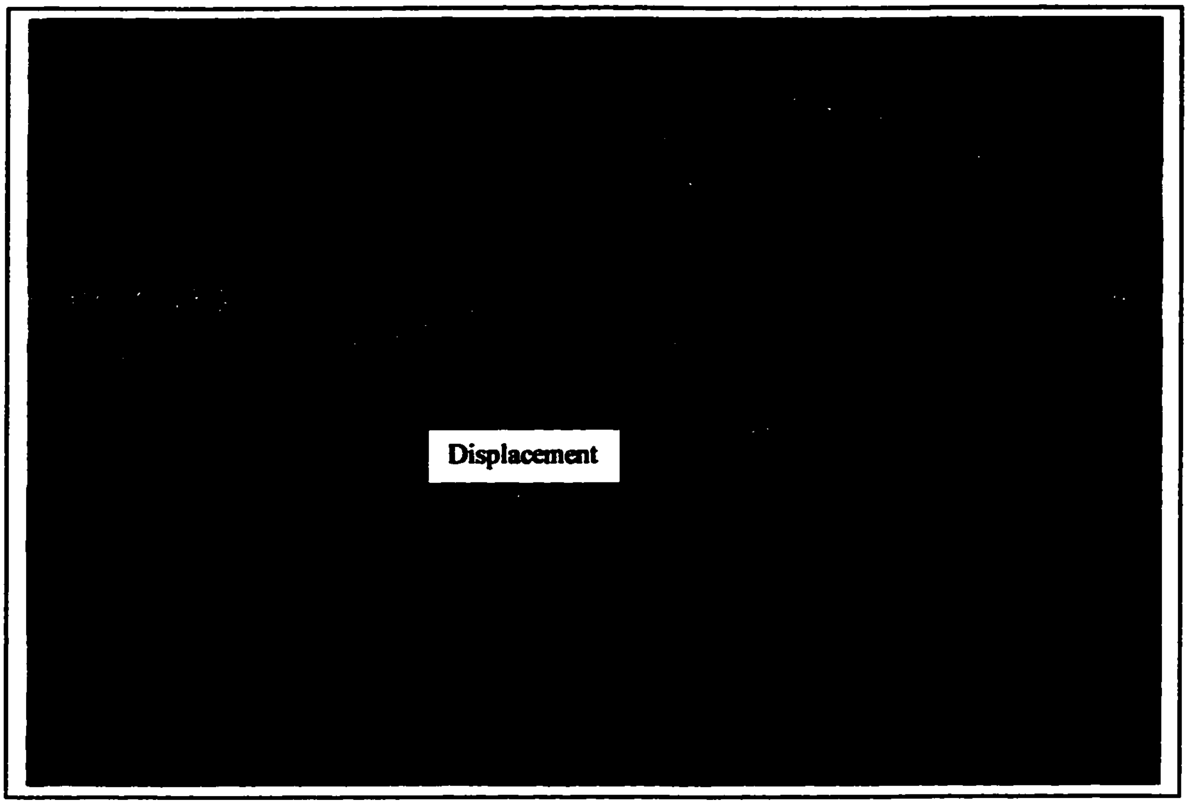


Figure 24. Photograph showing active creeping of the Thornton Beach Landslide. Fractures are approximately 1 to 5 centimeters apart (J. Baker).

specific time frames. By reorienting the displaced units to their pre-failure positions and by restoring the corresponding distance of 0.3 meters per year (erosion rate) to the shore, it is possible to predict when the landslide occurred. For example, to recreate the shoreline of approximately 500 years ago, 150 meters (500 years x 0.3 meters/year = 150 meters) of shoreline is added to the current shoreline. The shoreline is then reduced at the 0.3 meter rate at yearly time intervals to represent wave erosion, meanwhile, tracking the Factor of Safety. As the ancient shoreline is eroded, washing away stabilizing debris, the Factor of Safety drops until it equals 1, resulting in an approximation of the year the landslide occurred. The model first examines the shoreline as it existed approximately 500 years ago. The modeled shoreline is then eroded at 30 meter intervals, approximating the passage of 100 year increments, based on the 0.3 meter per year erosion rate. The Factor of Safety is calculated for each 100 year increment until it equals 1, thus arriving at the landslide's initiation date.

The Thornton Beach Landslide was modeled to calculate the Factor of Safety, test the imbricate slip plane theory, and determine the approximate initiation date of the landslide. The modeling was conducted under static conditions. The purpose of the modeling was to understand the effects of the Pacific Ocean erosional process on the landslide stability. The effect of seismic influences were not incorporated into the model, and this should be considered when interpreting the results of this study.

Had seismic influences been considered in the model, the results would likely have placed the landslide's initiation at an earlier point in time. The active faults near the landslide, such as the San Andreas Fault, suggest the probability of a large magnitude seismic event during the past 500 years. Such an event might have decreased the Factor of Safety of the landslide. Because the model was conducted under static conditions, the computed Factor of Safety and resulting landslide initiation date should be considered the most recent time the landslide could have occurred.

The following sketches show the scenario based on this dating model. The first sketch (Fig. 25) is a cross sectional drawing of the current Thornton Beach Landslide with the stratigraphic units and dips represented. The current slip plane location and the head scarp shown in Fig. 25 are also shown in dashed lines in Figs. 26 – 28 for reference.

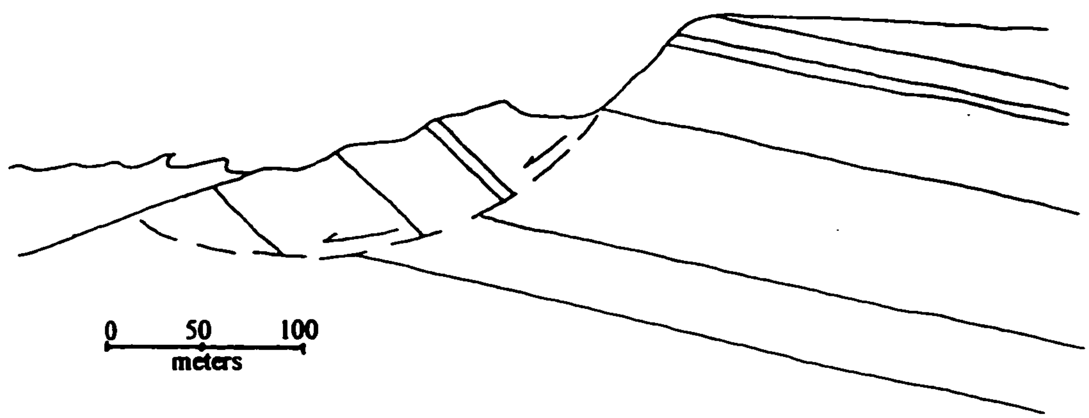


Figure 25. Sketch of current Thornton Beach Landslide.

Figure 26 shows the scenario where the displaced units have been restored to their original position. The dashed lines represent the current Thornton Beach Landslide. Figure 28 shows 150 meters of eroded shoreline added (500 years multiplied by an erosion rate of 0.3 meter/year) to represent the conditions 500 years in the past. Again, the current Thornton Beach Landslide is represented by dashed lines.

STABL5M was run after restoring 150 meters of displaced material to the slope, thus creating a model of the area as it appeared 500 years ago. Using the current Thornton Beach slip plane as the initiation point, the Factor of Safety of the area 500 years ago was approximately 1.26, stable compared to Factor of Safety values of the current landslide. The slip plane is shown in Figure 27 as dashed lines at the same initiation point as the current Thornton Beach Landslide.

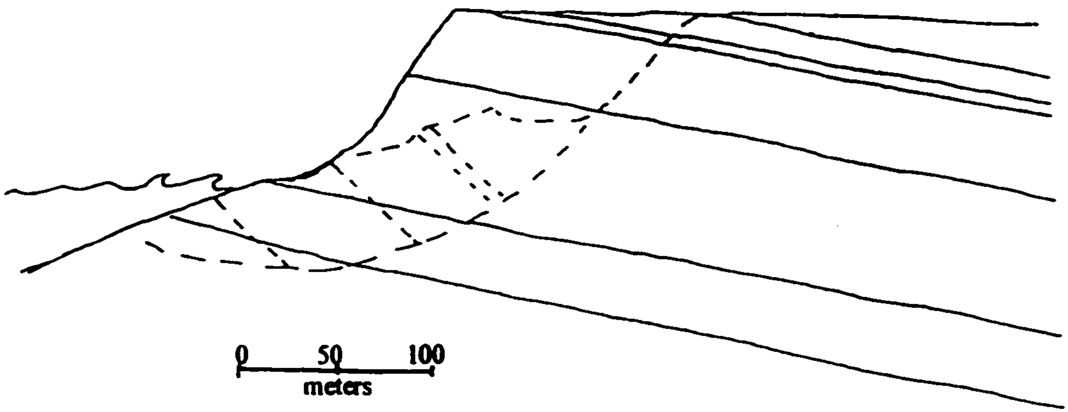


Figure 26. Sketch of Thornton Beach Landslide with displaced units restored to original position.

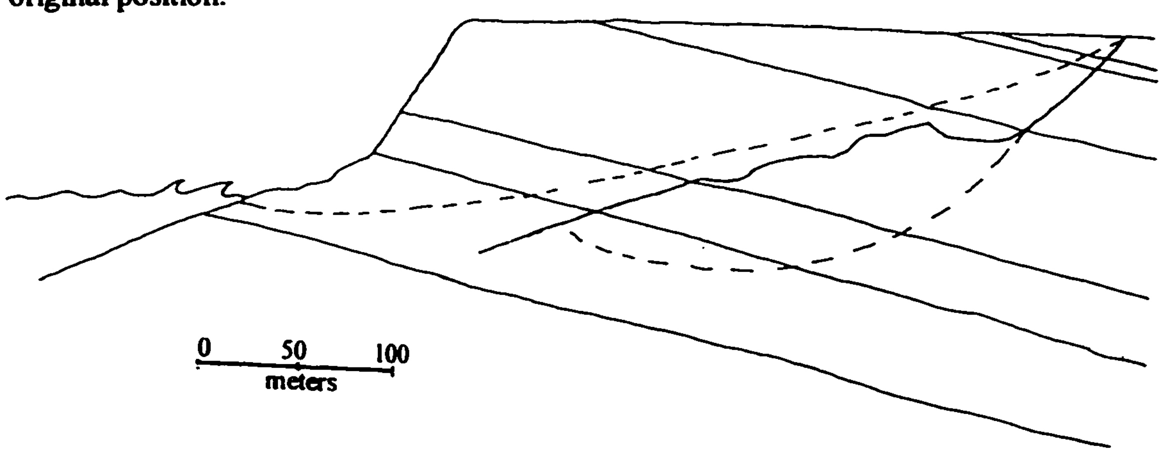


Figure 27. Sketch of Thornton Beach Landslide with 150 meters (500 feet) of restored units to represent 500 years ago.

Figure 28 shows a scenario representing the erosion of the land from along the shoreline, increasing the risk of landslide. This was created by removing 30 meters along the 500 year old coast line, representing its state 400 years ago. The dashed lines in Figure 28 represent the current Thornton Beach Landslide location.

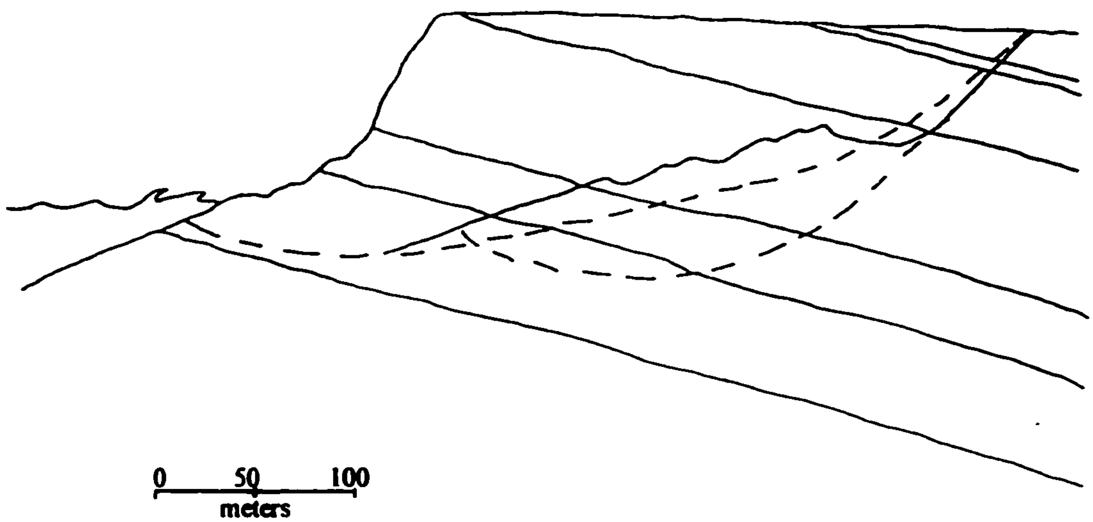


Figure 28. Sketch of Thornton Beach Landslide with 120 meters (400 feet) of restored units to represent 400 years ago.

The slip plane shown in Figure 28 has a Factor of Safety of 1.03, close to being unstable. Therefore, based on the modeling conducted, the Thornton Beach Landslide was initiated approximately 400 years in the past. The results of the computer modeling are shown in Appendix F. Because of the variability of the rainy winter season, the wave erosion rate, and the true nature of the area's topography during the actual time of the slippage, this model is only an approximation of the timing of the area's actual instability. However, this approximation can be useful in determining how instability has affected the current shoreline, and may be useful for predicting how slope stability will eventually affect the area.

Future Instability Modeling

To predict the stability of the area 20 years into the future, a model was created using the same assumption of a 0.3 meters per year erosion rate. Figure 29 is a sketch of the Thornton Beach Landslide according to this model, with 6 meters removed from the current shoreline. The dashed areas show the current Thornton Beach Landslide and the slip planes associated with the lowest Factor of Safety. This model produced a Factor of Safety of 0.71 to 0.86, indicating the area would be very unstable over the next two decades. The lowest Factor of Safety (0.71) slip plane was located in the general area of the current slip plane on the Olympic Golf Course, and the highest factor of safety (0.86) slip plane was located approximately 365 meters inland.

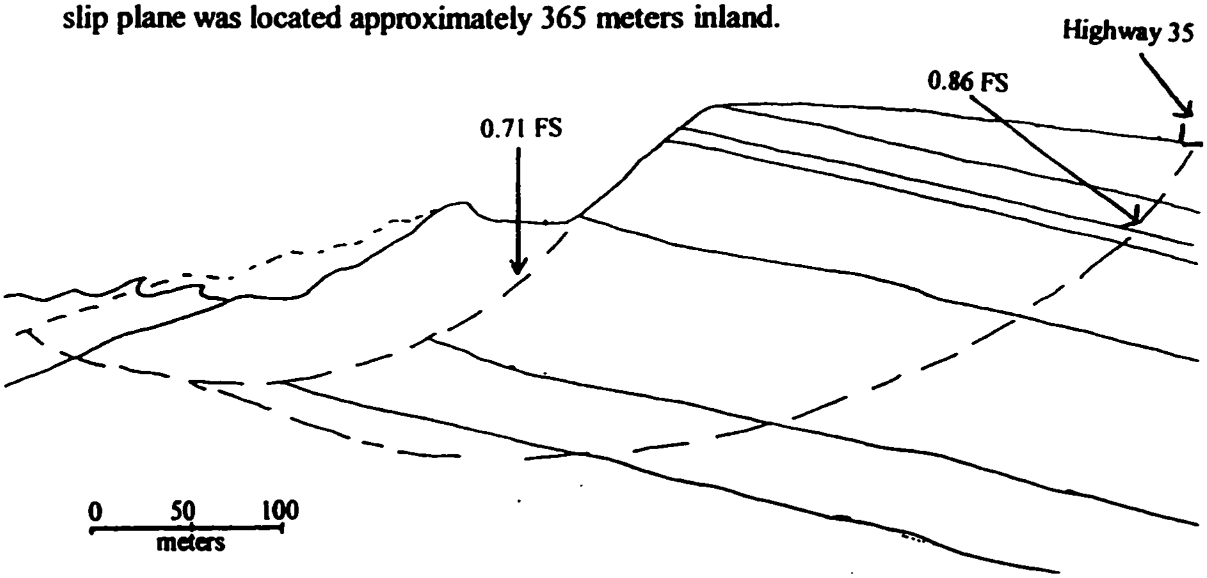


Figure 29. Sketch of Thornton Beach Landslide with 6 meters (20 feet) eroded away to represent 20 years into the future.

Conclusion

Based on field observations, analysis of aerial photos, and computer modeling of the deep rotational landslide at the Thornton Beach State Park, it is concluded that the area is unstable, especially in the rainy winter months or during high groundwater periods. Computer modeling of the deep rotational landslide at Thornton Beach supports the estimation of its age of approximately 400 years. Due to constant wave erosion, the mass of the landslide has decreased, making the area farther inland unstable as well. Currently, the Olympic Golf Course head scarp is growing in a southern direction, will cause further damage to Highway 35, and eventually become the primary slip plane in the Thornton Beach area. Figure 30 shows the Thornton Beach area with a dashed line representing the slip plane location as modeled with approximately 6 meters of erosion from the current shoreline. As shown in the figure, the slip plane location is near Highway 35, which has already been damaged by landsliding, and is likely to be further damaged by landsliding in the future. Additional structures in peril are the Olympic Golf Course and the stables at the Thornton Beach State Park. Computer modeling shows this area to have Factor of Safety values of less than one and are particularly susceptible to landslides.

The Thornton Beach Landslide is unstable, with Factors of Safety close to 1.00 during the rainy season. The landslide will continue to become less stable as coastal erosion removes material from the toe. Furthermore, computer modeling suggests that the main instability will shift from the Thornton Beach Landslide failure plane to the

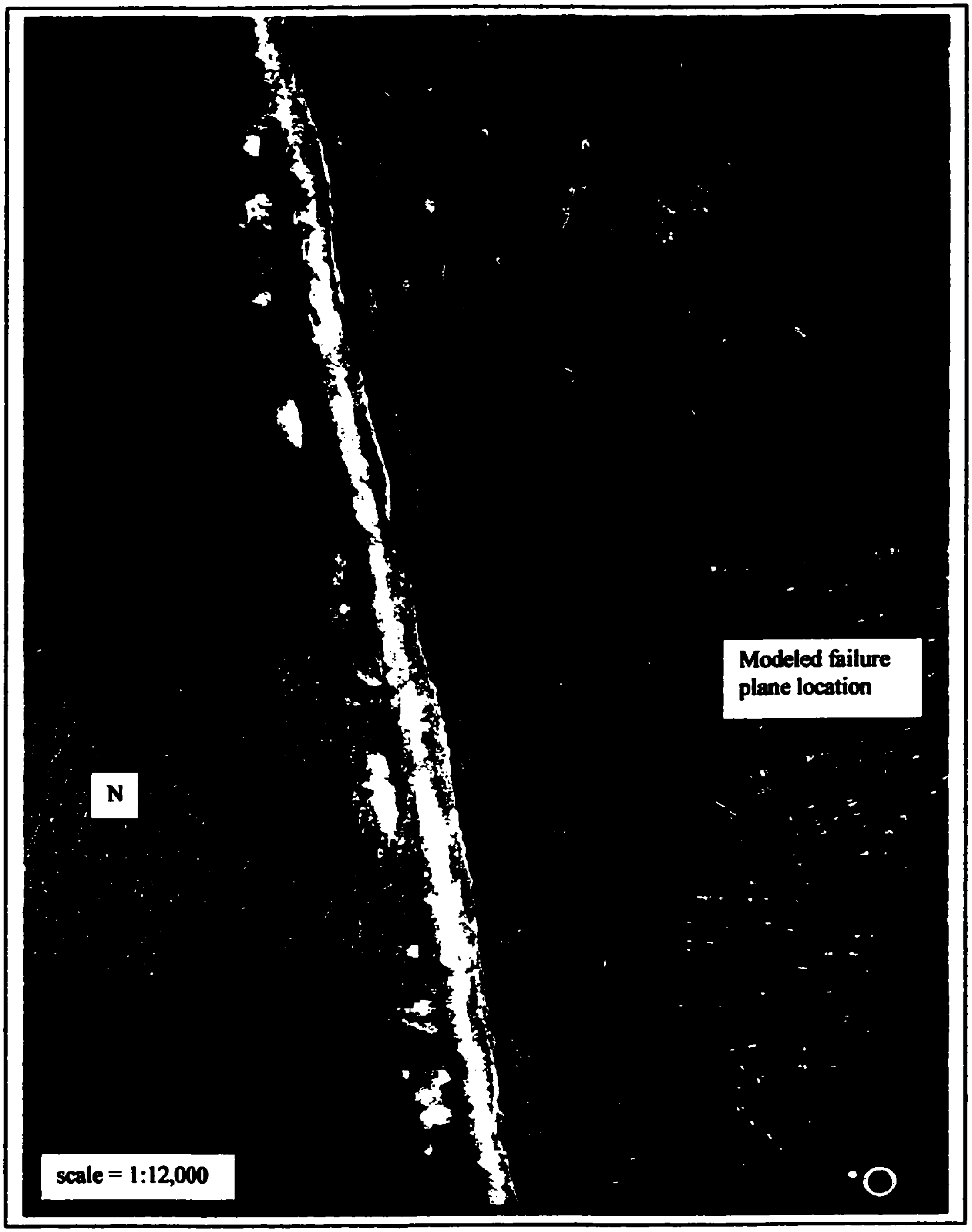


Figure 30. 1997 Aerial Photograph showing location of failure plane with a Factor of Safety of 0.86 modeled with 6 meters of erosion.

Olympic Golf Course Landslide failure plane farther inland and closer to Highway 35. If the failure plane does daylight in the Pacific Ocean, as proposed by Bonilla (1960), confirmed by Baker (2000), and modeled in this paper, this will further destabilize the landslide.

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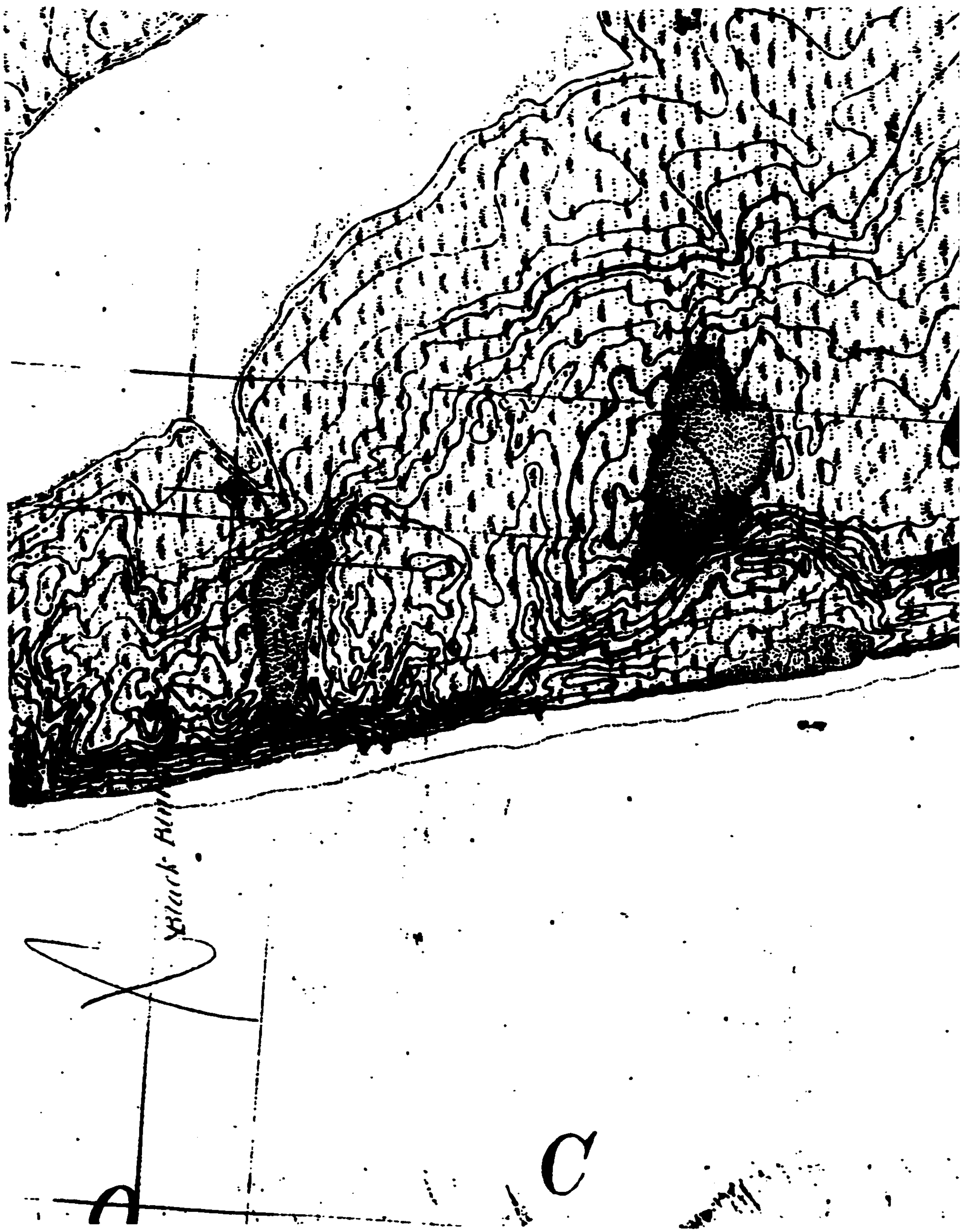
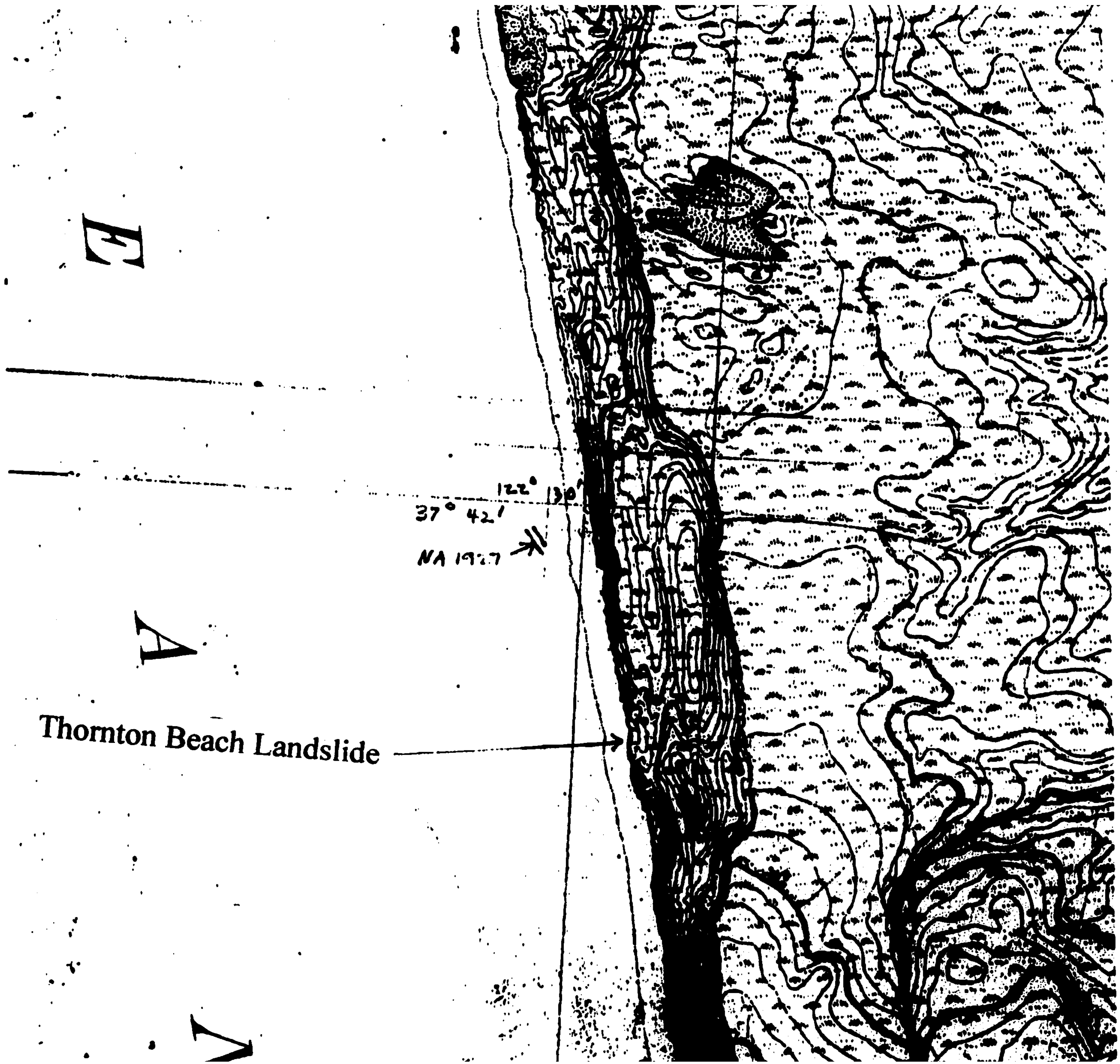
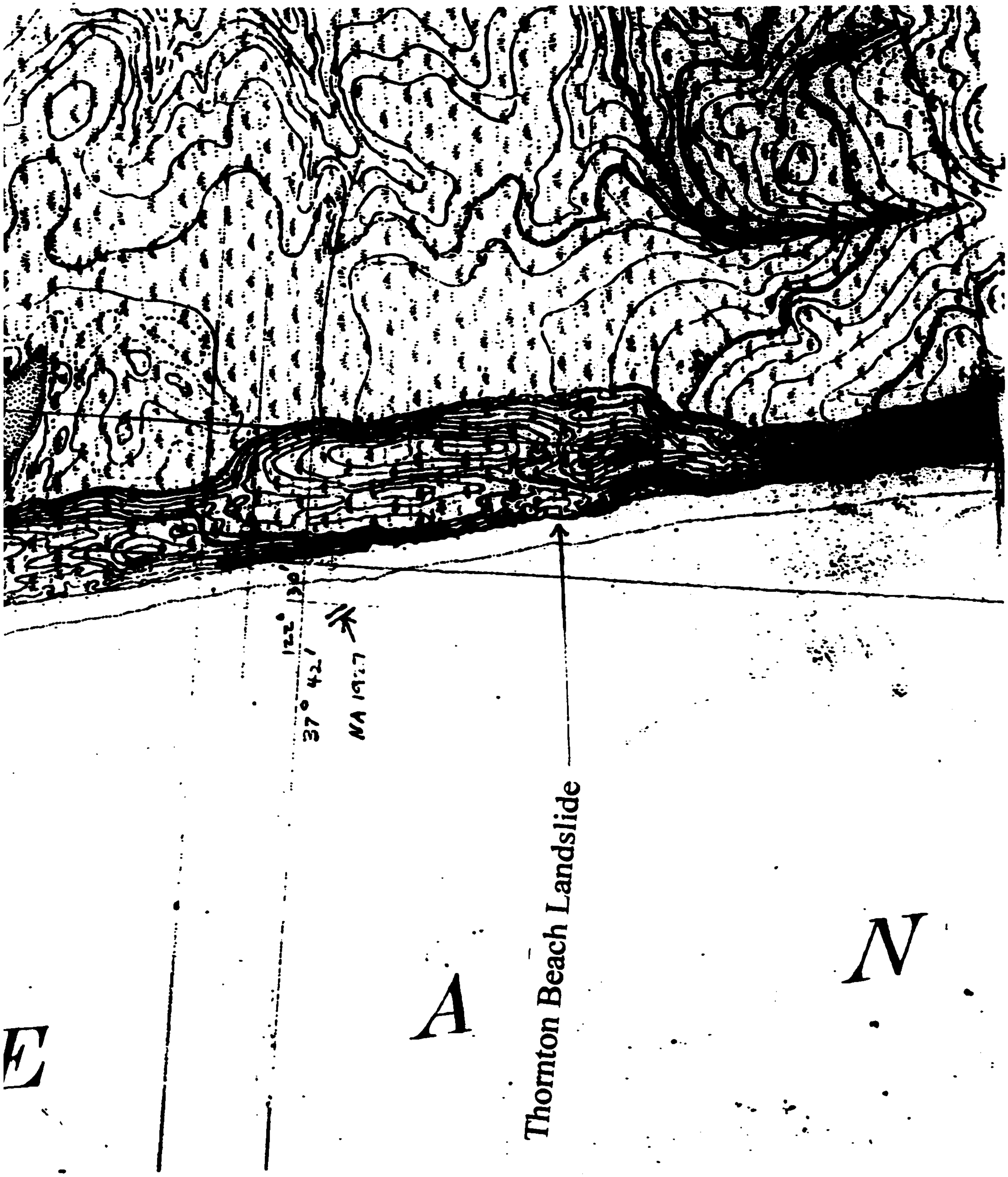
APPENDIX A
1852 San Francisco Topographic Map

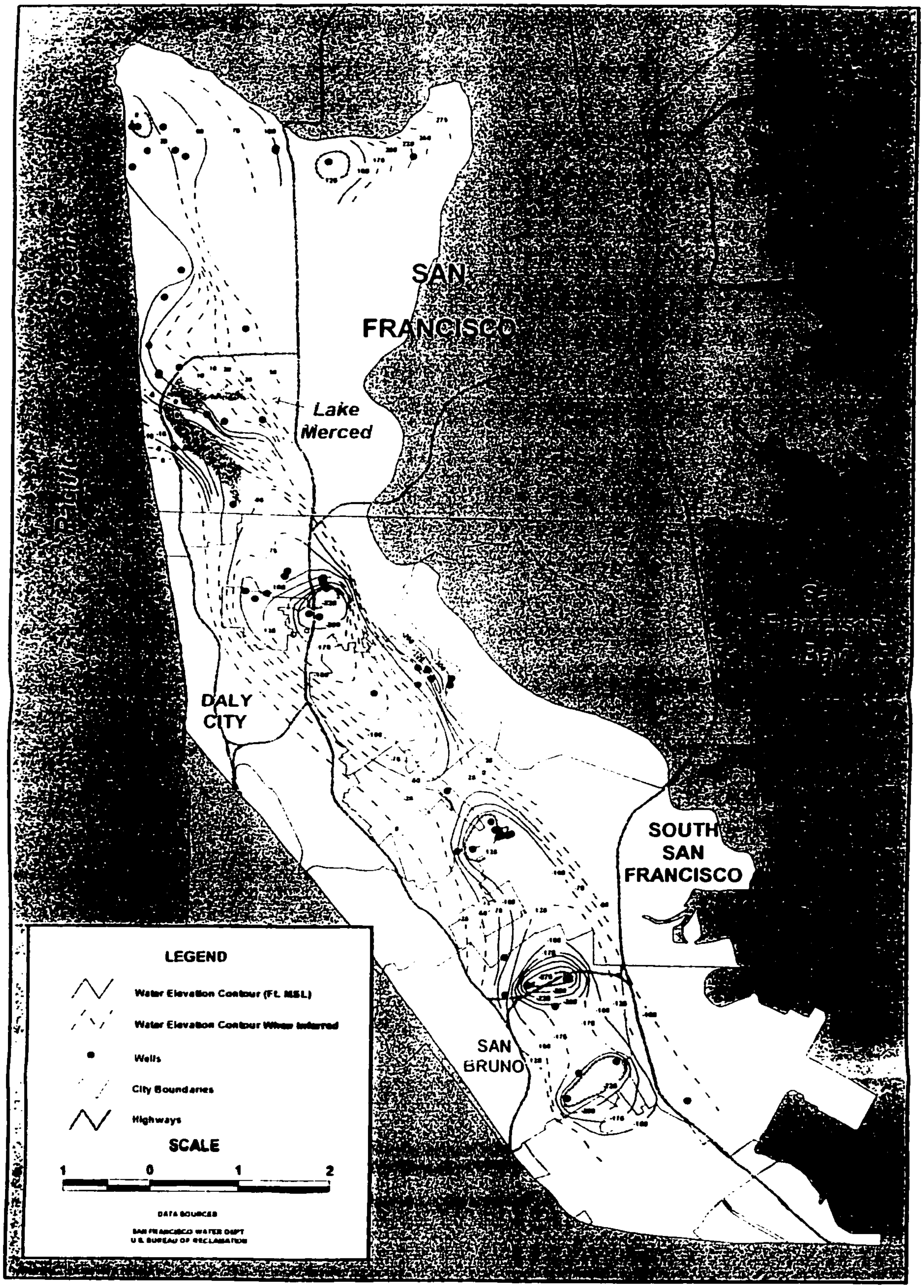

Black Run
A
C



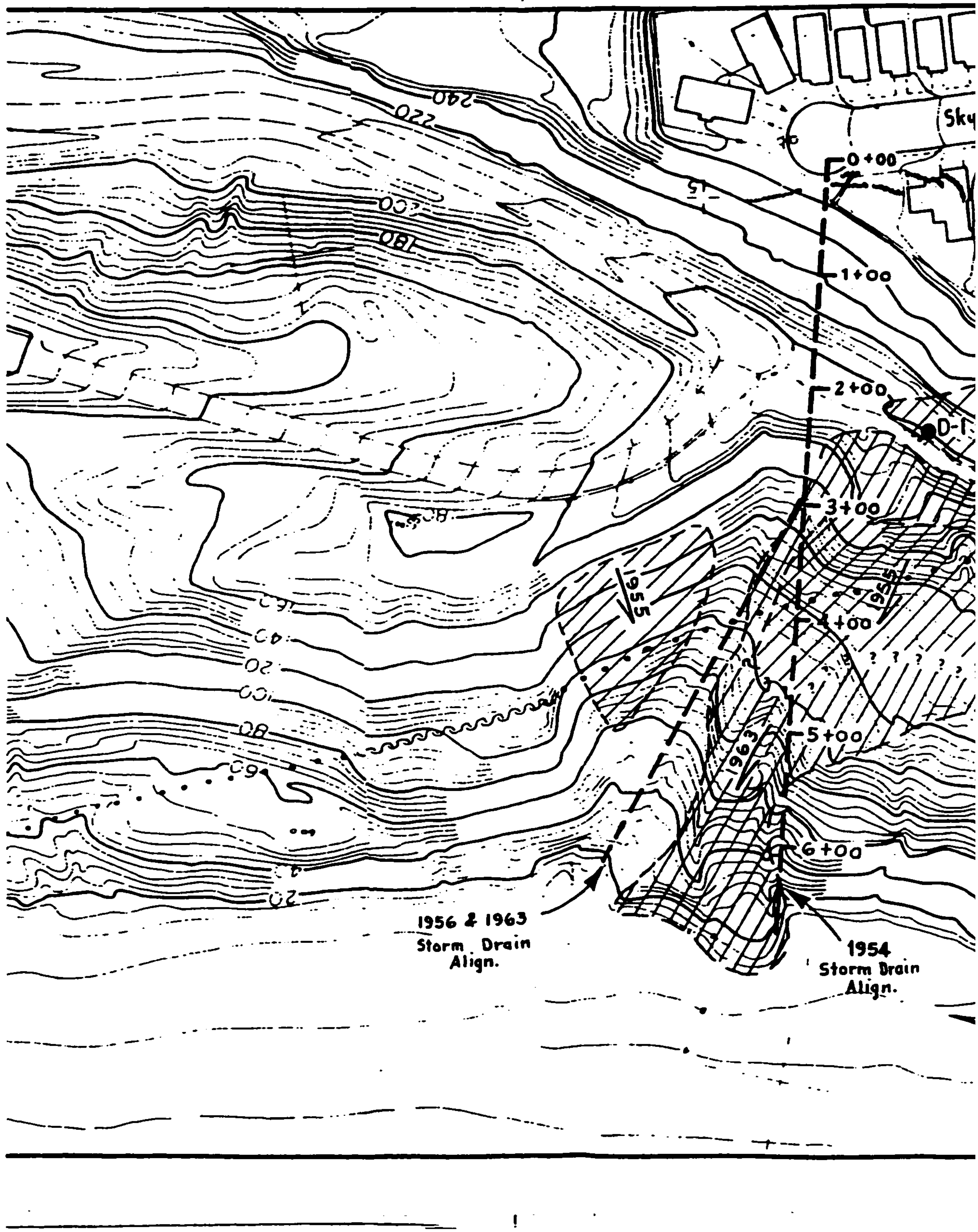
E
A
Thornton Beach Landslide
122° 30'
37° 42'
NA 1927


Thornton Beach Landslide
E
A
N
37° 42'

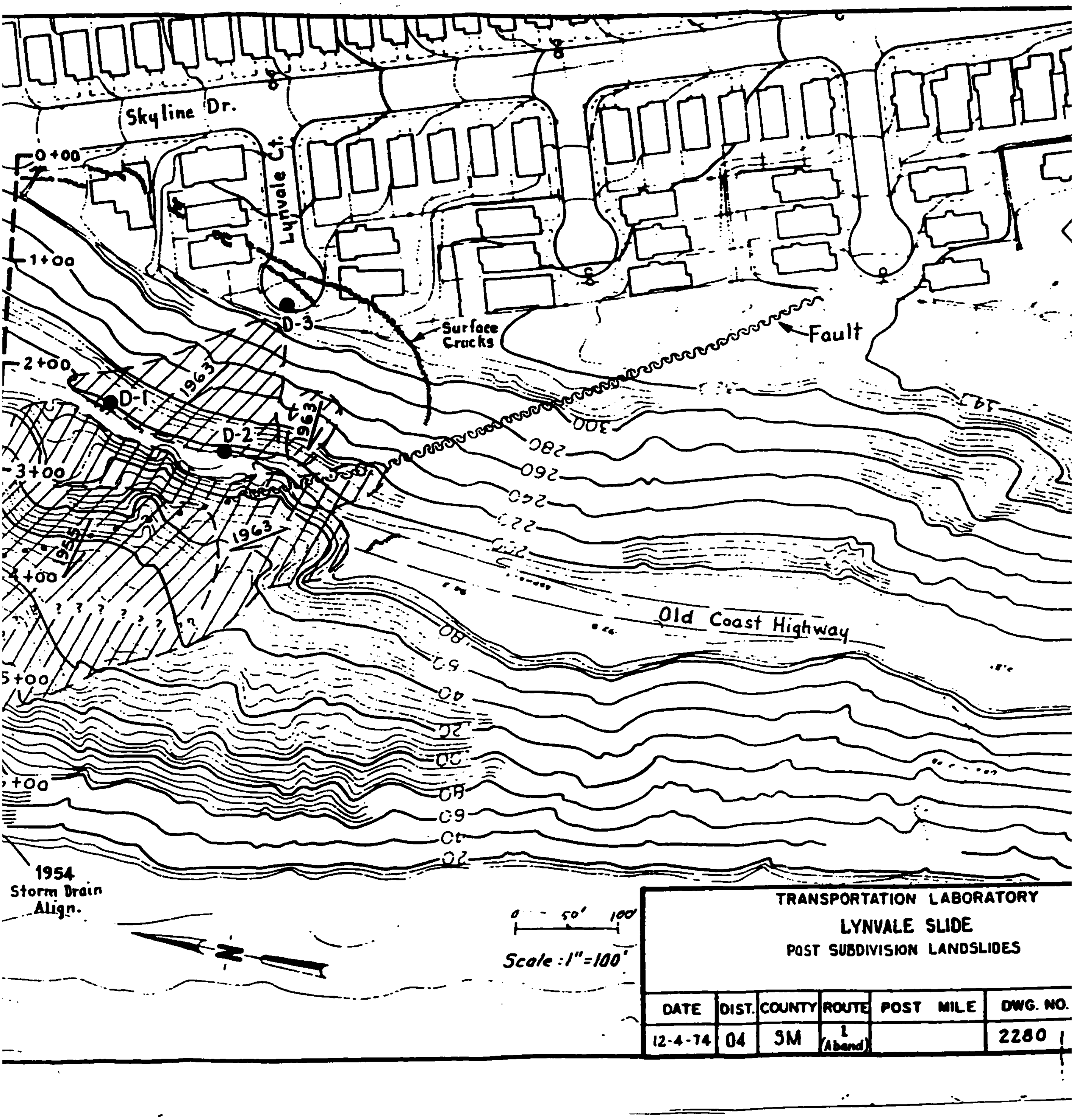
APPENDIX B
Westside Basin Groundwater Management Plan
Water Table Map of San Francisco Area
(Bookman – Edmonston Engineering, Inc., 1996)

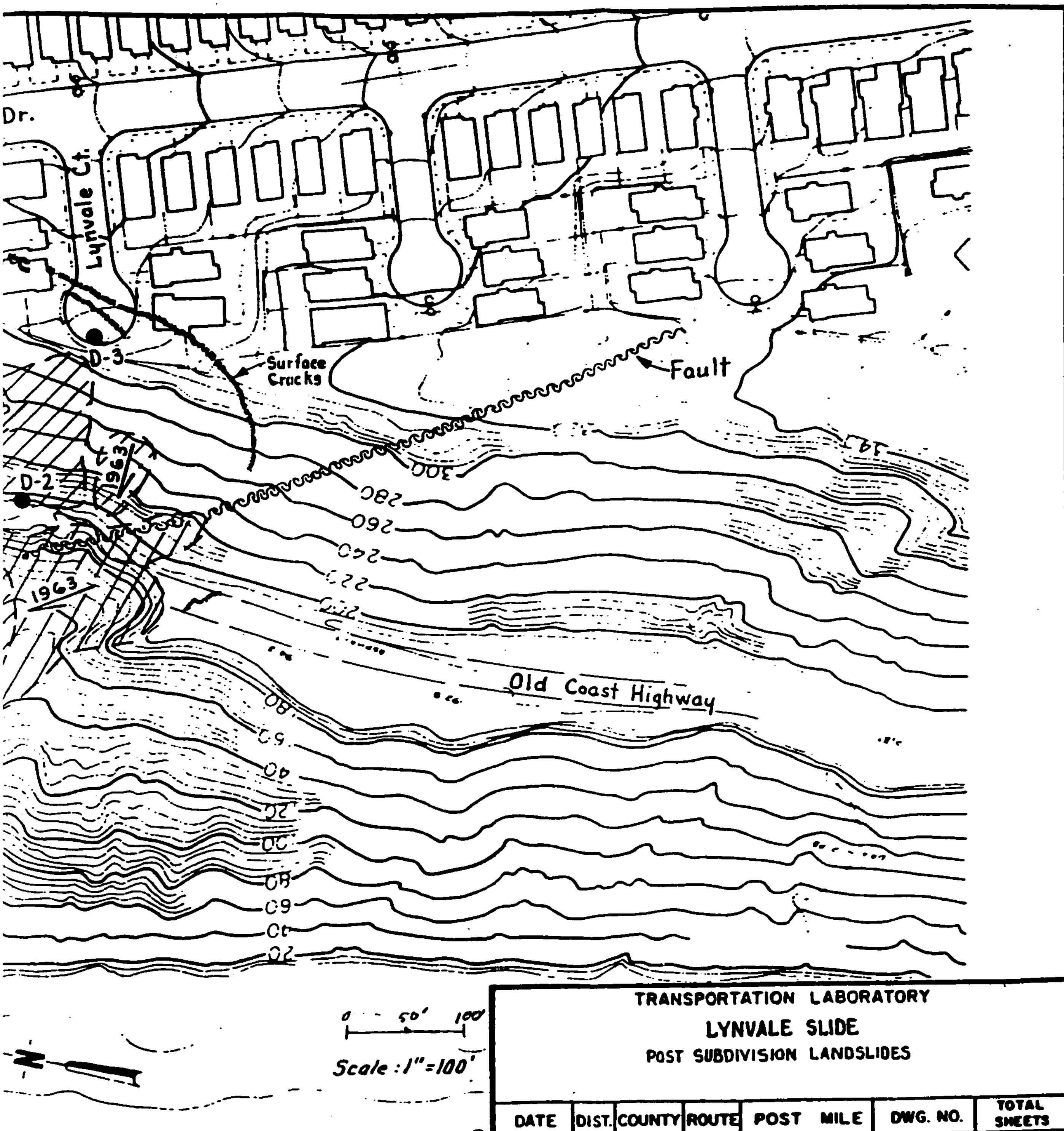

SAN
FRANCISCO
Lake
Merced
DALY
CITY
SOUTH
SAN
FRANCISCO
SAN
BRUNO
LEGEND
Water Elevation Contour (Ft. MSL)
Wells
City Boundaries
Highways
SCALE
1
0
1
2
DATA SOURCES
SAN FRANCISCO WATER DEPT
U.S. BUREAU OF RECLAMATION

APPENDIX C
Borehole Information on Lynvale Court
(Caltrans, 1974)

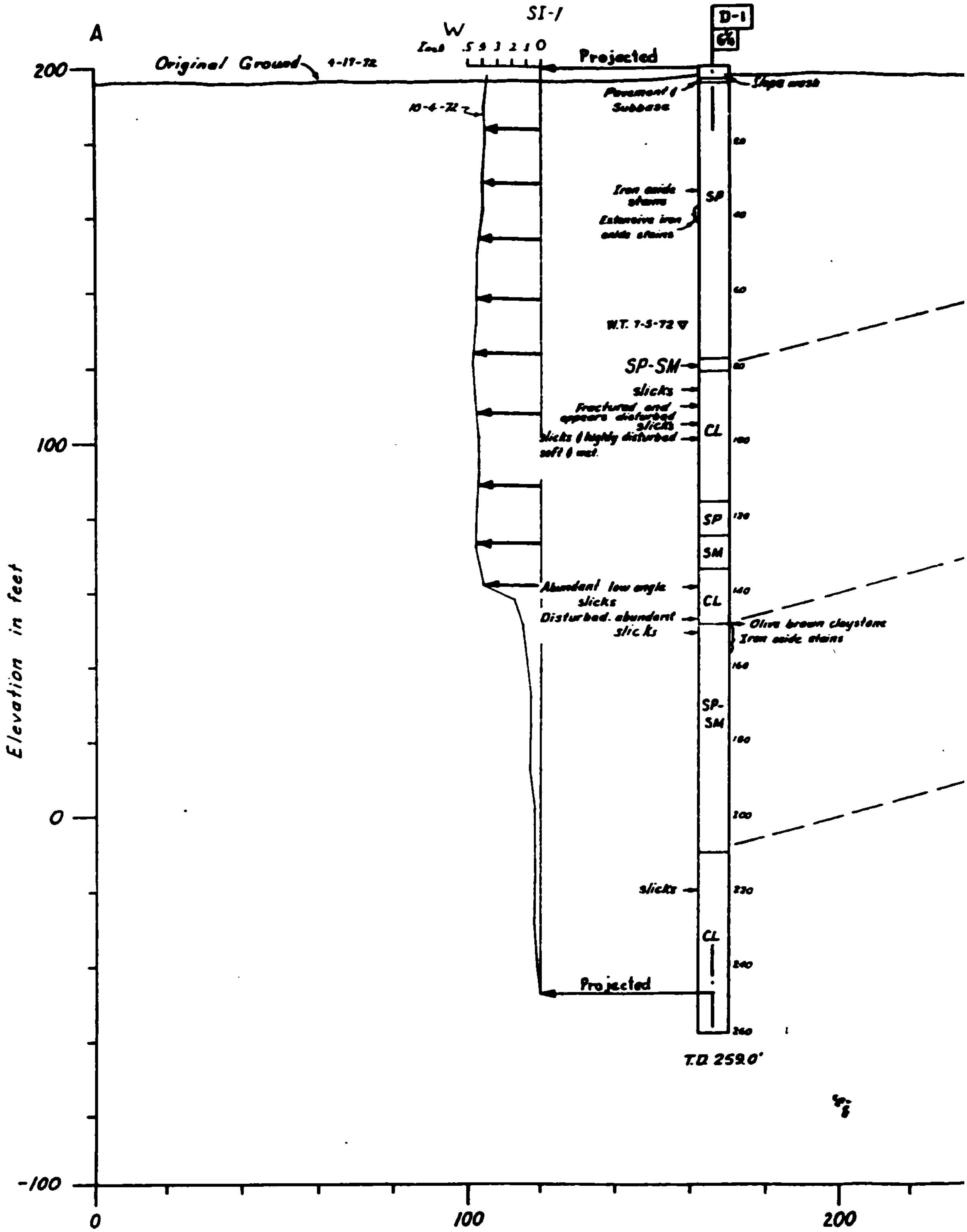


Sky
0+00
1+00
2+00
D-1
3+00
4+00
5+00
6+00
1955
1963
1956 & 1963
Storm Drain
Align.
1954
Storm Drain
Align.

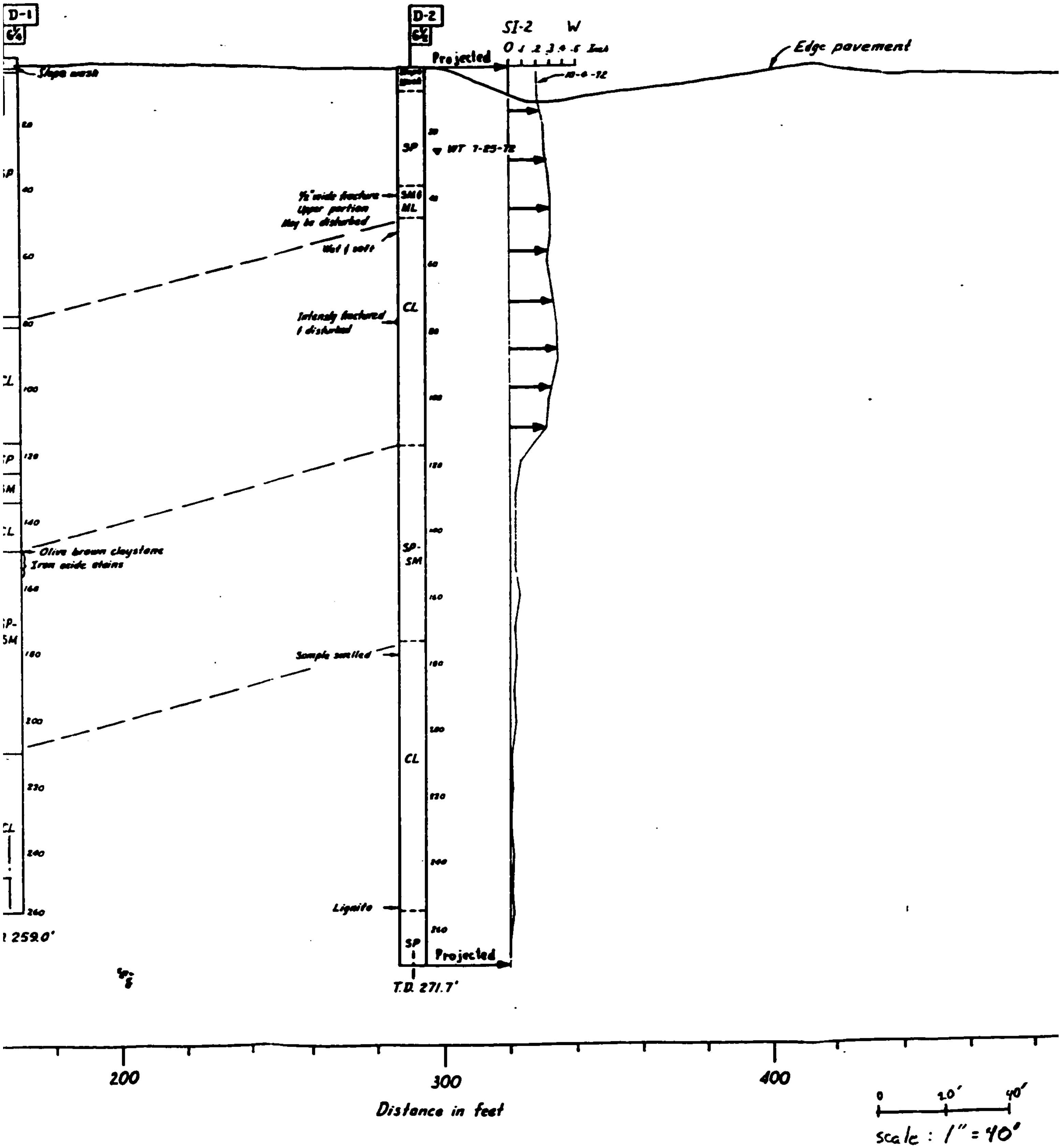

Skyline Dr.
Lynvale Ct.
0+00
1+00
2+00
3+00
4+00
5+00
D-1
D-2
D-3
1963
1963
1963
1955
Surface Cracks
Fault
300
280
260
240
Old Coast Highway
1954
Storm Drain
Align.
0
50'
100'
Scale: 1"=100'
TRANSPORTATION LABORATORY
LYNVALE SLIDE
POST SUBDIVISION LANDSLIDES
DATE
12-4-74
DIST.
04
COUNTY
SM
ROUTE
1 (Aband)
POST MILE
DWG. NO.
2280



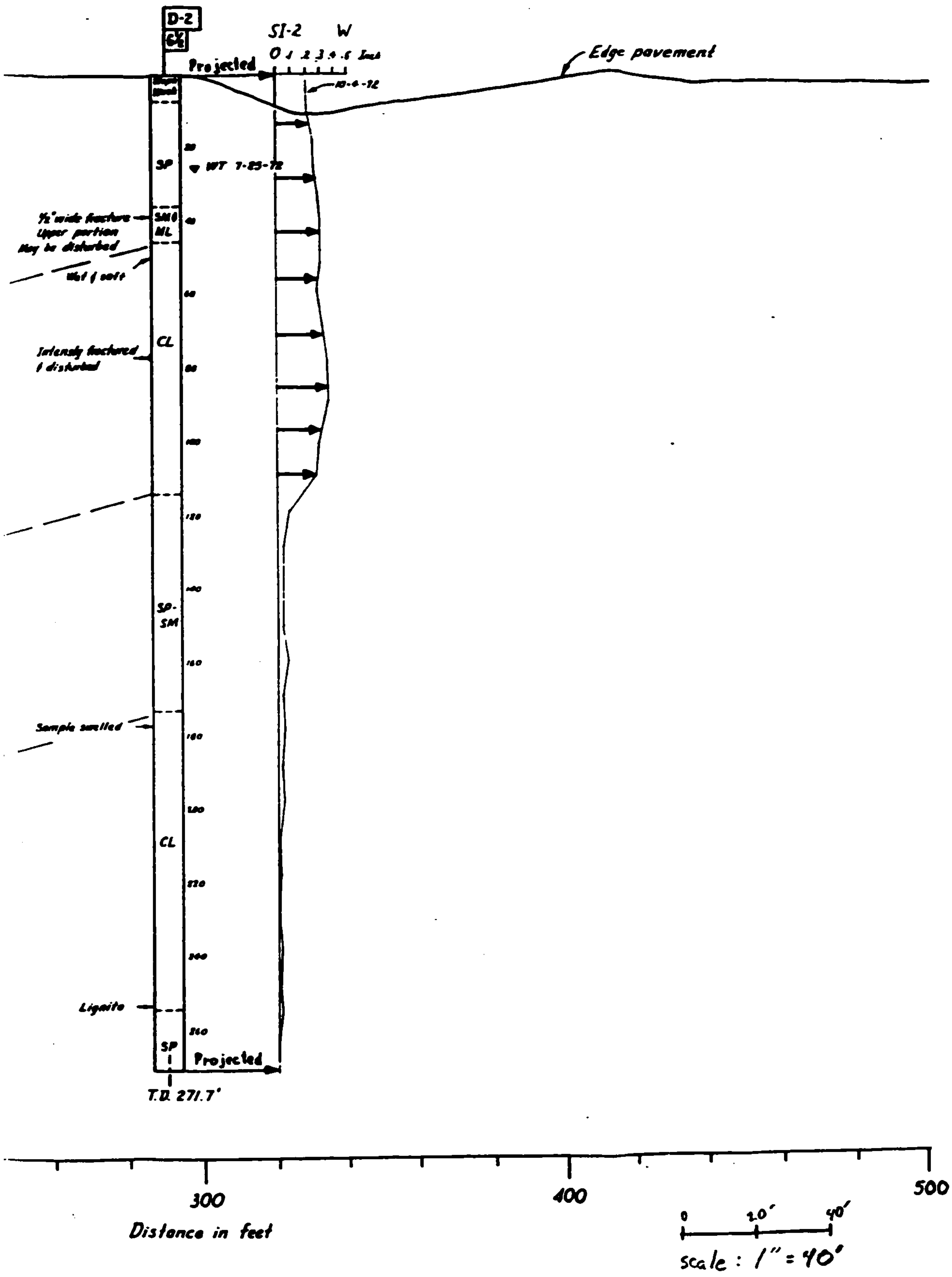
TRANSPORTATION LABORATORY						
LYNVALE SLIDE						
POST SUBDIVISION LANDSLIDES						
DATE	DIST.	COUNTY	ROUTE	POST MILE	DWG. NO.	TOTAL SHEETS
12-4-74	04	SM	1 (Aband)		2280	3 of 6



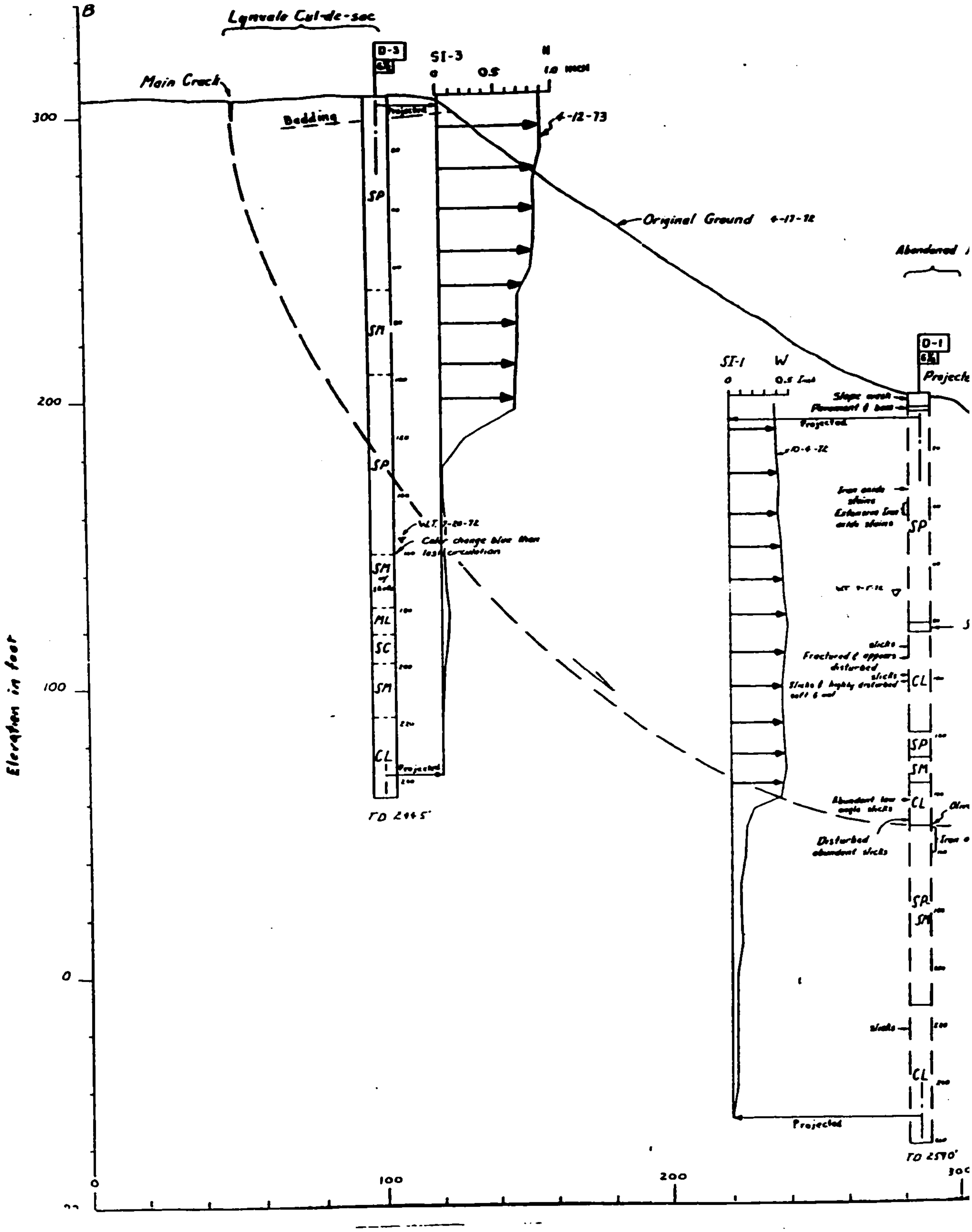
A
SI-1
W
D-1
Projected
Original Ground 4-19-72
10-4-72
Pavement & Subbase
Slope wash
Iron oxide stains
Extensive iron oxide stains
SP
W.T. 7-5-72
SP-SM
slicks
Fractured and appears disturbed
slicks
slicks & highly disturbed soft & wet.
CL
SP
SM
Abundant low angle slicks
Disturbed. abundant slicks
Olive brown claystone
Iron oxide stains
SP-SM
slicks
CL
Projected
T.D. 259.0'
Elevation in feet
200
100
0
-100
0
100
200



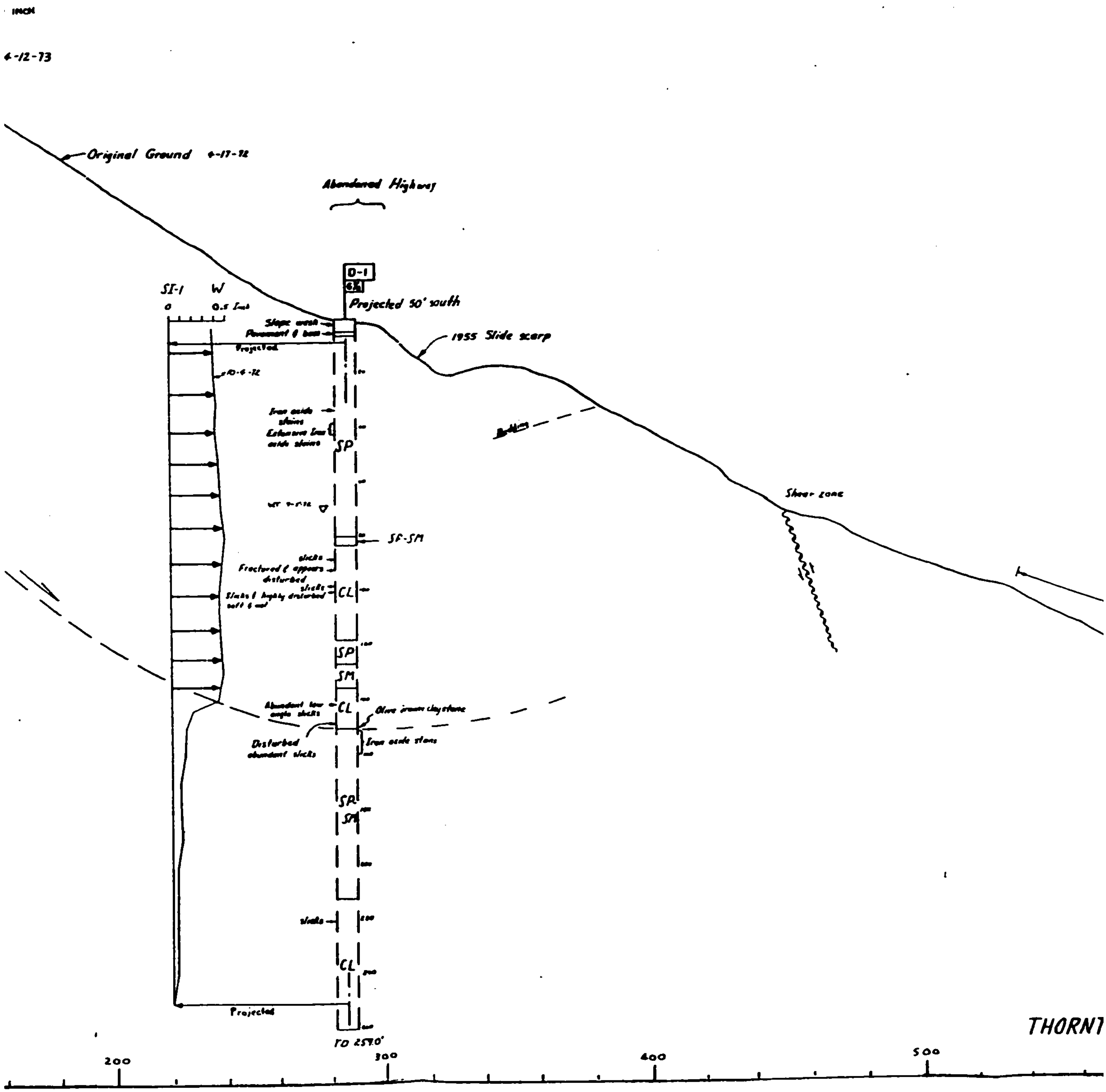
THORNTON BLUFFS LANDSLIDE

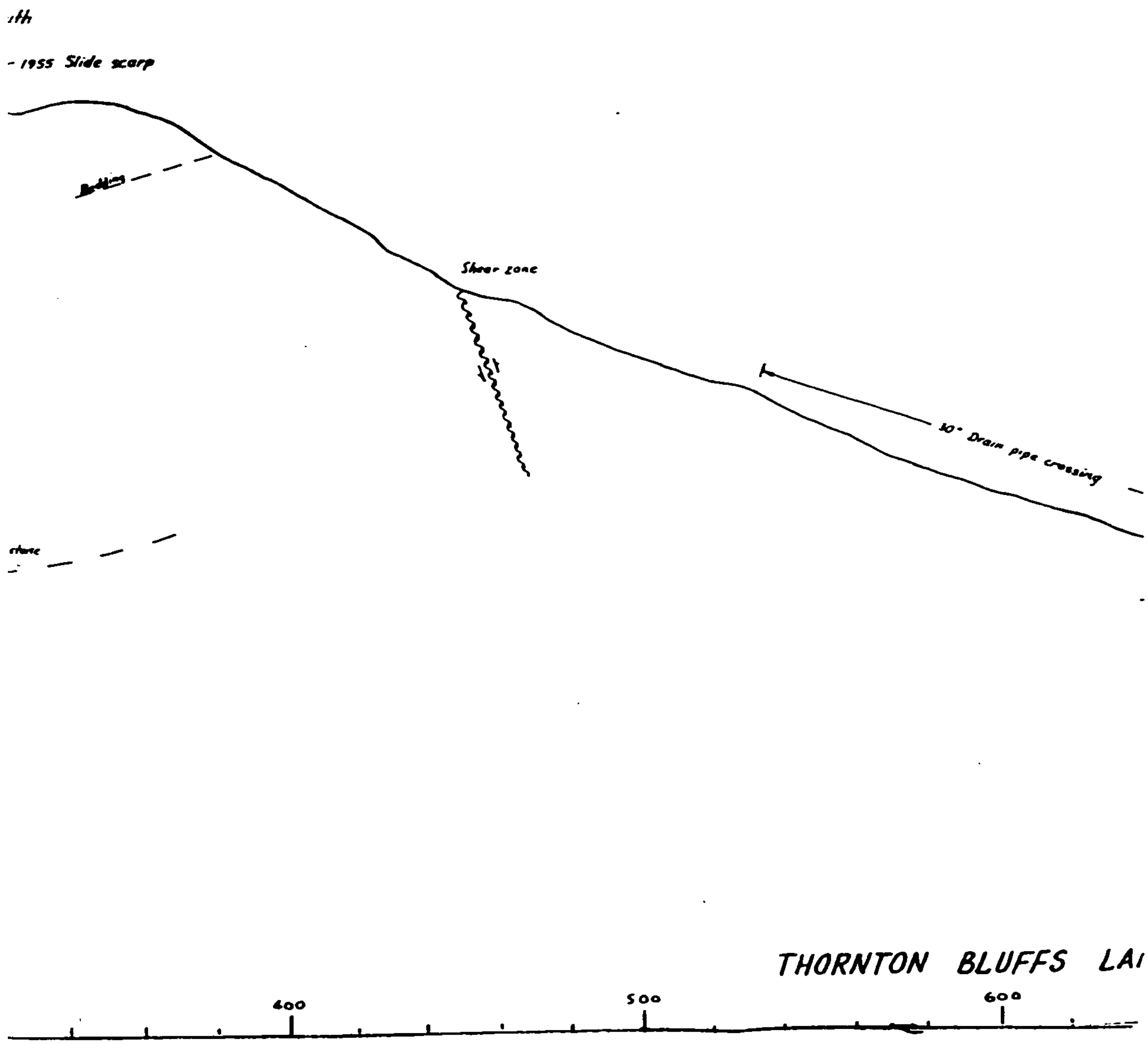


HORNTON BLUFFS LANDSLIDE



B
Lynvale Cul-de-sac
Main Crack
Bedding
D-3
SI-3
0.5
1.0 inch
4-12-73
Original Ground
Abandoned
D-1
SI-1
W
Projected
10-4-72
SP
SM
CL
ML
SC
Color change blue then lost circulation
Slope wash
Pavement & base
Fractured & appears disturbed
Disturbed abundant slicks
Abundant low angle slicks
slicks
TD 244.5'
TD 259.0'
Elevation in feet
300
200
100
0
100
200


4-12-73
Original Ground 4-17-72
Abandoned Highway
D-1
Projected 50' south
SI-1
W
0
0.5
Slope wash
Pavement & base
Projected
1955 Slide scarp
SP
SP-SM
CL
SP
SM
CL
Olive brown claystone
Iron oxide stains
Disturbed abundant slicks
SP
SM
slicks
CL
Projected
TD 257.0'
Shear zone
THORNT
200
300
400
500



ıth
- 1955 Slide scarp
Shear zone
30" Drain pipe crossing
stone
THORNTON BLUFFS LA
400
500
600

APPENDIX D
San Francisco Monthly Rainfall Totals

SAN FRANCISCO MONTHLY RAINFALL
in Centimeters

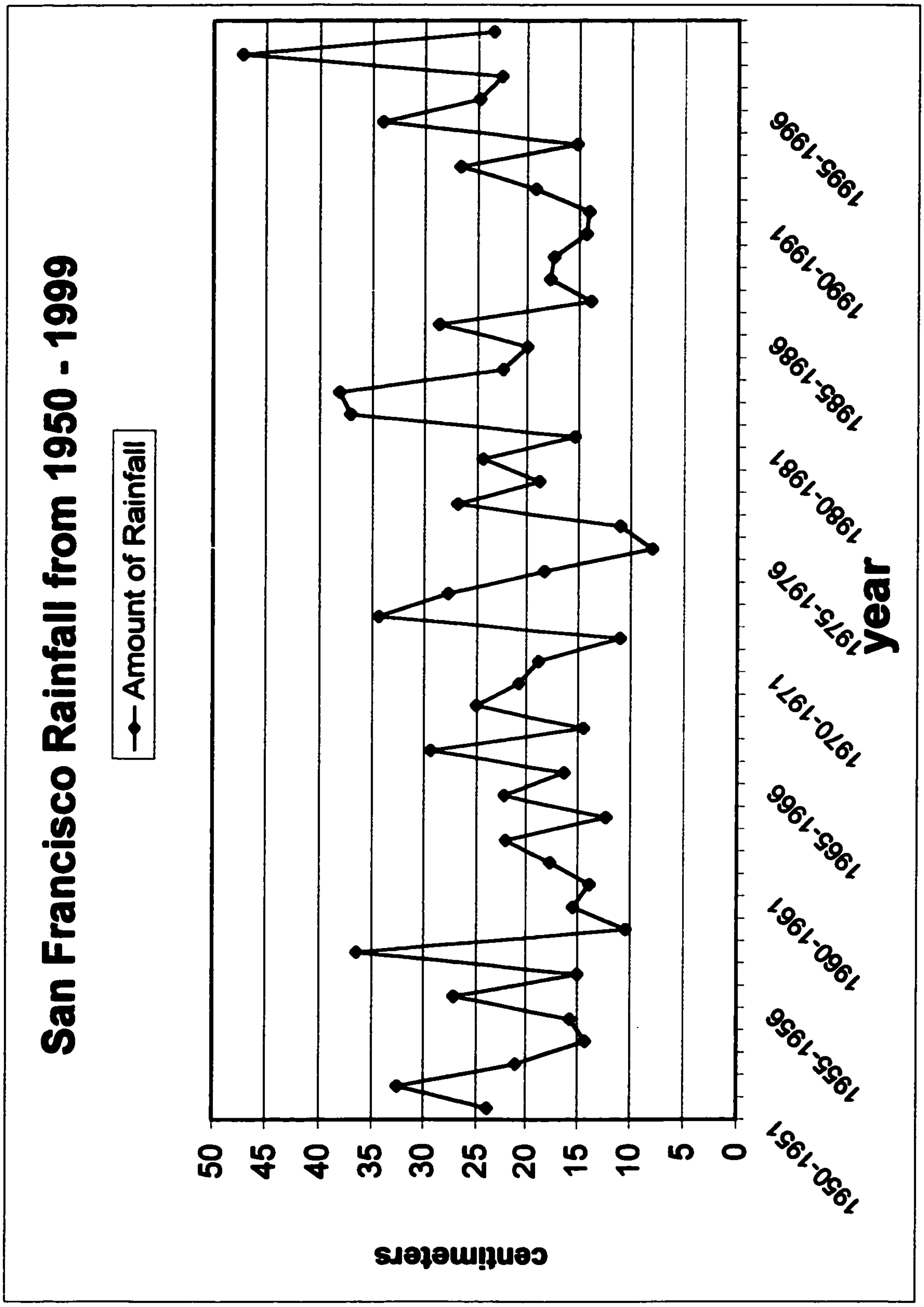
(Updated 6-30-99)

Winter Year	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
1950-1951	0.0	0.0	0.0	6.9	12.6	15.3	11.2	7.6	3.4	2.3	1.7	0.1	61.0
1951-1952	0.0	1.1	0.2	2.1	8.5	20.1	27.2	6.7	12.4	2.7	0.8	1.0	82.7
1952-1953	0.0	0.0	0.0	0.2	6.1	23.0	8.3	0.1	4.6	8.7	1.0	1.5	63.6
1953-1954	0.0	0.2	0.0	0.9	4.8	2.1	7.9	6.1	11.6	2.1	0.3	0.4	38.2
1954-1955	0.1	0.5	0.0	0.6	6.5	14.4	10.3	3.0	0.7	3.8	0.1	0.0	40.0
1955-1956	0.1	0.0	0.1	0.1	6.0	29.1	22.1	5.2	0.3	4.3	1.7	0.1	69.0
1956-1957	0.0	0.0	0.8	2.9	0.1	0.9	7.2	9.1	6.1	2.8	8.1	0.2	38.2
1957-1958	0.0	0.0	3.7	8.8	2.9	9.1	11.1	19.8	20.9	13.9	2.2	0.2	92.7
1958-1959	0.1	0.0	0.1	0.3	0.2	3.8	10.1	10.3	0.8	0.9	0.1	0.0	26.6
1959-1960	0.0	0.1	5.2	0.0	0.0	4.3	10.3	9.1	5.2	2.9	2.2	0.0	39.3
1960-1961	0.0	0.0	0.0	1.2	8.5	5.9	7.1	2.4	5.8	2.0	2.2	0.1	35.2
1961-1962	0.0	0.1	0.6	0.2	11.3	5.4	2.7	16.7	7.0	0.9	0.0	0.0	44.8
1962-1963	0.0	0.2	0.6	14.0	1.5	7.1	8.5	4.9	9.8	8.5	1.1	0.0	56.3
1963-1964	0.0	0.0	0.2	3.5	8.9	2.2	8.6	0.5	5.4	0.0	0.6	1.4	31.3
1964-1965	0.0	0.0	0.0	4.8	10.1	13.6	10.1	2.4	7.4	8.2	0.0	0.0	56.6
1965-1966	0.1	1.2	0.0	0.0	12.2	8.9	8.3	6.9	2.0	0.9	0.5	0.4	41.5
1966-1967	0.2	0.3	0.3	0.0	12.2	9.8	24.1	0.6	11.0	12.4	0.2	3.6	74.7
1967-1968	0.0	0.0	0.1	1.3	2.8	5.4	11.5	5.8	8.0	1.2	0.6	0.0	36.7
1968-1969	0.0	0.1	0.2	1.6	6.8	9.9	19.7	18.4	2.6	4.4	0.0	0.1	63.7
1969-1970	0.0	0.0	0.0	6.6	1.1	15.6	19.8	4.0	3.9	0.2	0.1	1.4	52.8
1970-1971	0.0	0.0	0.0	2.1	16.4	13.7	5.2	0.7	7.4	1.8	0.5	0.0	47.7
1971-1972	0.0	0.0	0.6	0.3	4.9	10.0	3.4	5.4	0.6	2.7	0.0	0.3	28.1
1972-1973	0.0	0.1	1.4	13.7	16.3	9.0	23.8	16.1	6.7	0.1	0.2	0.0	87.3
1973-1974	0.0	0.0	0.8	4.6	21.9	10.7	9.3	3.9	12.9	6.1	0.0	0.3	70.5
1974-1975	1.9	0.0	0.0	2.3	1.0	4.6	7.2	10.9	14.9	3.3	0.1	0.1	46.4
1975-1976	0.5	0.1	0.0	7.0	1.1	1.3	0.8	5.0	2.6	1.8	0.0	0.1	20.2
1976-1977	0.0	2.0	1.3	1.0	3.0	6.4	4.7	2.3	5.9	0.1	1.4	0.0	28.1
1977-1978	0.0	0.1	2.4	0.4	5.6	8.4	15.1	10.5	15.0	10.7	0.0	0.0	68.2
1978-1979	0.0	0.0	0.5	0.0	4.2	2.3	18.9	14.2	5.0	2.2	0.4	0.0	47.6
1979-1980	0.2	0.0	0.0	4.9	9.3	10.5	11.8	17.2	4.4	3.3	0.6	0.1	62.2
1980-1981	0.1	0.0	0.0	0.0	0.7	7.8	12.6	5.3	11.8	0.4	0.3	0.0	39.1
1981-1982	0.0	0.0	0.6	5.3	12.9	13.8	24.3	9.7	19.8	7.7	0.0	0.2	94.2
1982-1983	0.0	0.0	1.8	7.1	14.3	5.6	14.7	20.5	23.0	8.8	1.2	0.0	97.0
1983-1984	0.0	0.2	1.7	0.7	20.8	19.6	1.3	5.9	3.4	2.3	0.4	0.8	57.1
1984-1985	0.0	0.6	0.3	7.5	18.9	5.3	1.5	5.0	10.0	0.7	0.2	0.8	50.8
1985-1986	0.0	0.0	1.0	2.0	12.3	6.3	12.1	21.1	15.9	1.9	0.3	0.0	72.8
1986-1987	0.1	0.0	3.4	0.3	0.5	4.2	10.8	9.6	5.9	0.4	0.2	0.0	35.2
1987-1988	0.0	0.0	0.0	2.7	7.8	12.9	12.5	1.0	0.2	4.4	1.7	1.8	45.1
1988-1989	0.0	0.0	0.0	1.6	9.4	10.7	3.2	3.8	13.4	1.8	0.2	0.2	44.3
1989-1990	0.0	0.1	2.5	3.0	3.4	0.0	10.2	6.2	3.4	1.5	6.0	0.0	36.4
1990-1991	0.0	0.1	0.3	0.5	1.3	4.9	1.5	8.4	15.0	2.7	0.9	0.1	35.8
1991-1992	0.0	1.1	0.0	6.0	1.3	5.9	5.3	16.1	11.2	1.0	0.0	1.0	48.8
1992-1993	0.0	0.1	0.0	2.9	1.0	15.3	24.9	11.4	7.4	1.8	2.2	0.7	67.7
1993-1994	0.0	0.0	0.0	0.8	5.5	5.7	7.0	12.4	0.9	2.8	3.3	0.2	38.7
1994-1995	0.0	0.0	0.6	0.8	26.6	6.8	22.8	0.6	20.0	4.1	2.5	1.6	86.4
1995-1996	0.0	0.0	0.0	0.2	0.2	20.7	17.0	13.4	3.3	4.0	4.5	0.0	63.2
1996-1997	0.0	0.0	0.1	2.7	11.9	19.4	19.2	0.8	1.5	0.7	0.4	0.8	57.4
1997-1998	0.0	1.9	0.1	2.6	17.7	7.0	30.7	37.8	6.5	5.4	10.0	0.4	120.0
1998-1999	0.0	0.0	0.2	2.3	10.2	3.6	11.2	18.7	5.9	6.6	0.6	0.3	59.7
Monthly Averag	0.07	0.20	0.64	2.89	7.83	9.36	12.02	8.84	7.81	3.56	1.25	0.41	
Percent of total	0.1%	0.4%	1.2%	5.3%	14.3%	17.1%	21.9%	16.1%	14.2%	6.5%	2.3%	0.7%	

Yearly Average	54.87

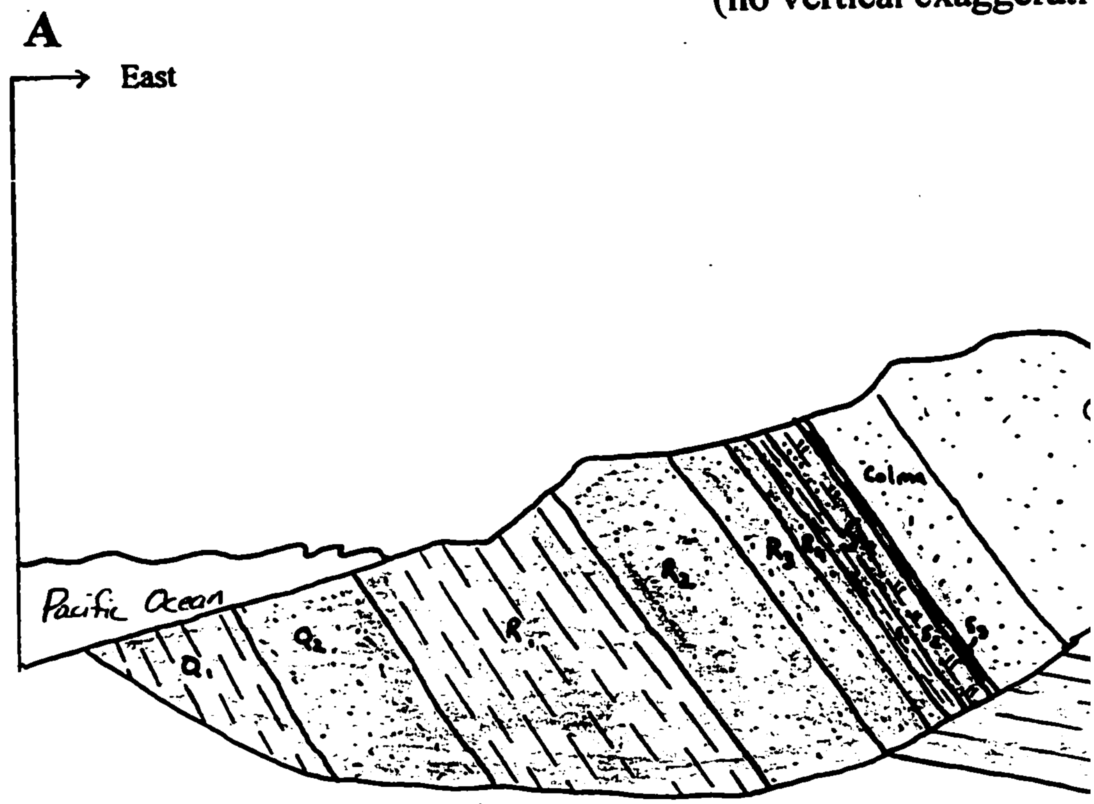
Average	54.87

Source: National Oceanic and Atmospheric Administration

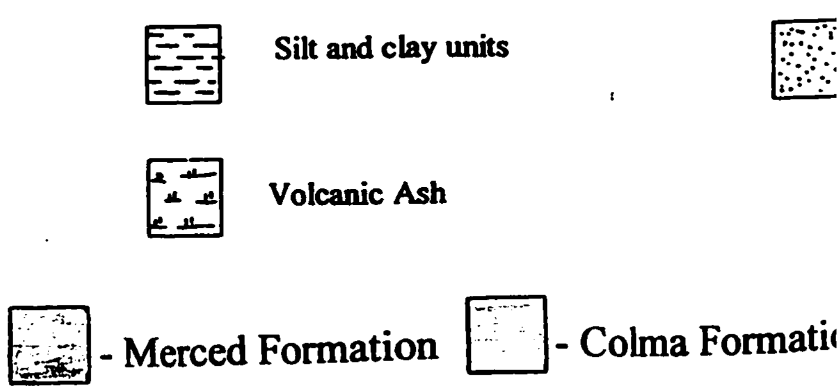

San Francisco Rainfall from 1950 - 1999
Amount of Rainfall
centimeters
50
45
40
35
30
25
20
15
10
5
0
1950-1951
1955-1956
1960-1961
1965-1966
1970-1971
1975-1976
1980-1981
1985-1986
1990-1991
1995-1996
year

APPENDIX E
Geologic Section of Thornton Beach Landslide

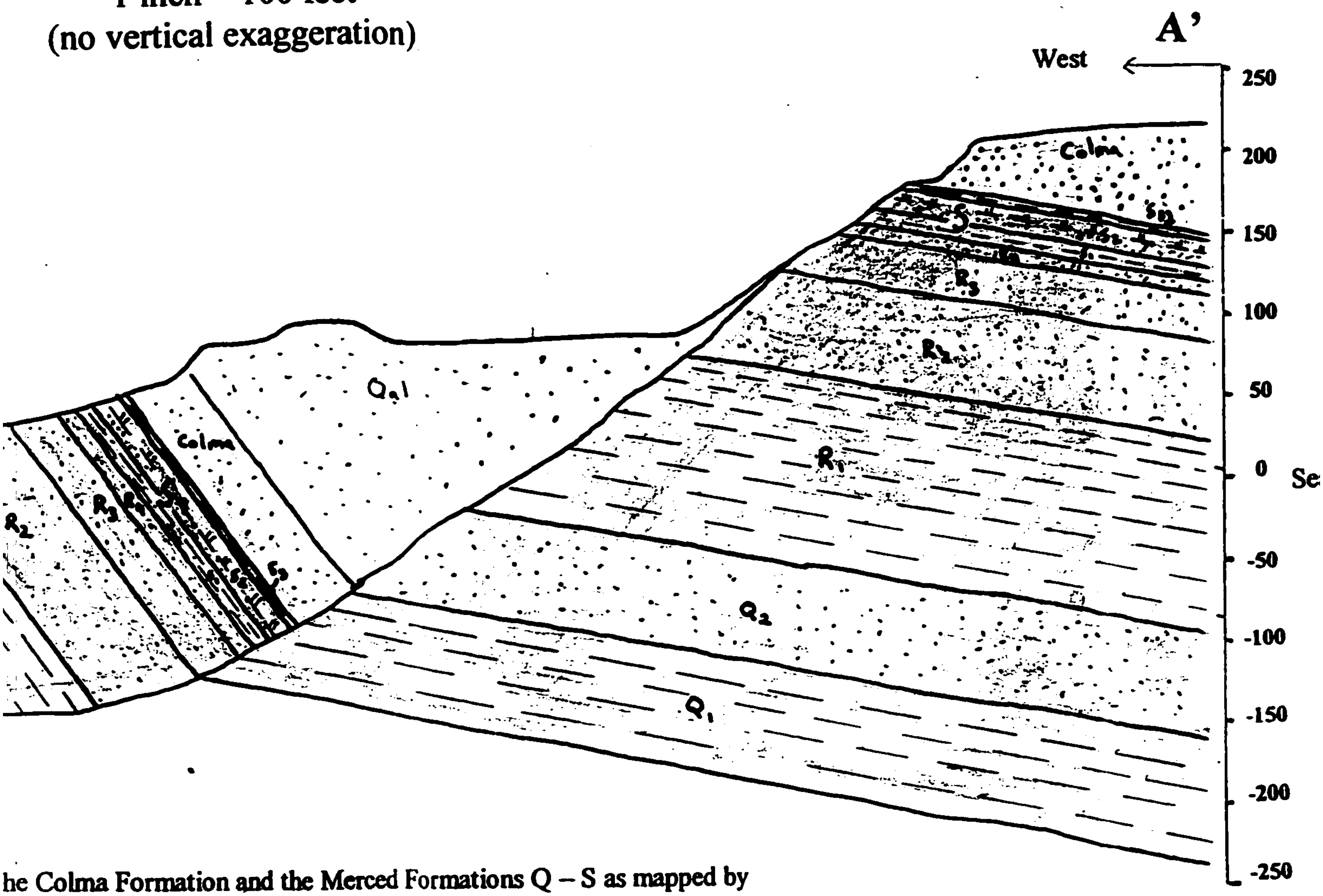
Geologic Section
Of
The Thornton Beach Lan
Daly City, Californi
1 inch = 100 feet
(no vertical exaggerati



Section shows the Colma Formation and the Merc
Clifton and Hunter, (



Geologic Section
Of
The Thornton Beach Landslide
Daly City, California
1 inch = 100 feet
(no vertical exaggeration)



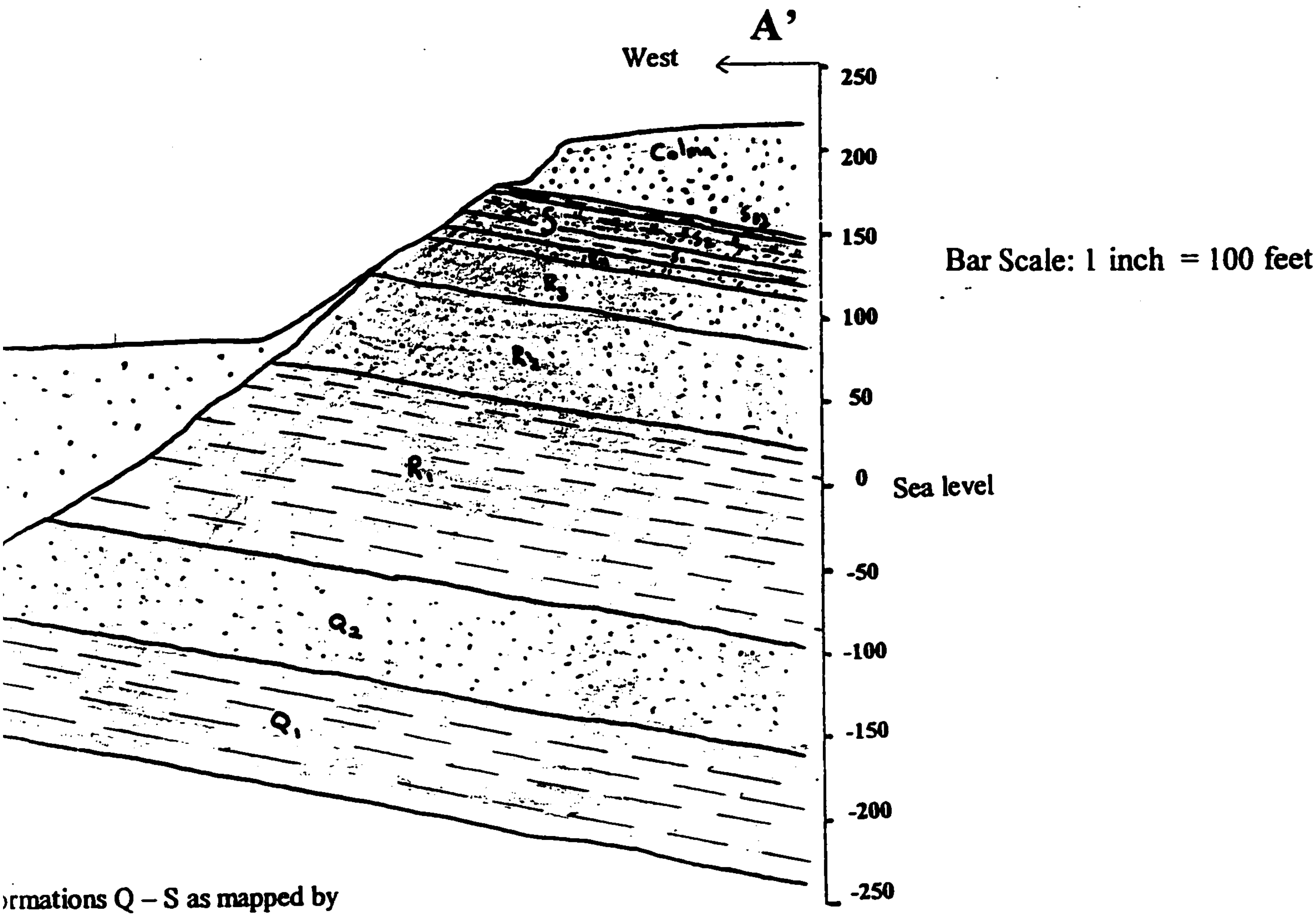
he Colma Formation and the Merced Formations Q – S as mapped by
Clifton and Hunter, (1987).

ay units

Sand units

Ash

on - Colma Formation - Quaternary Alluvium

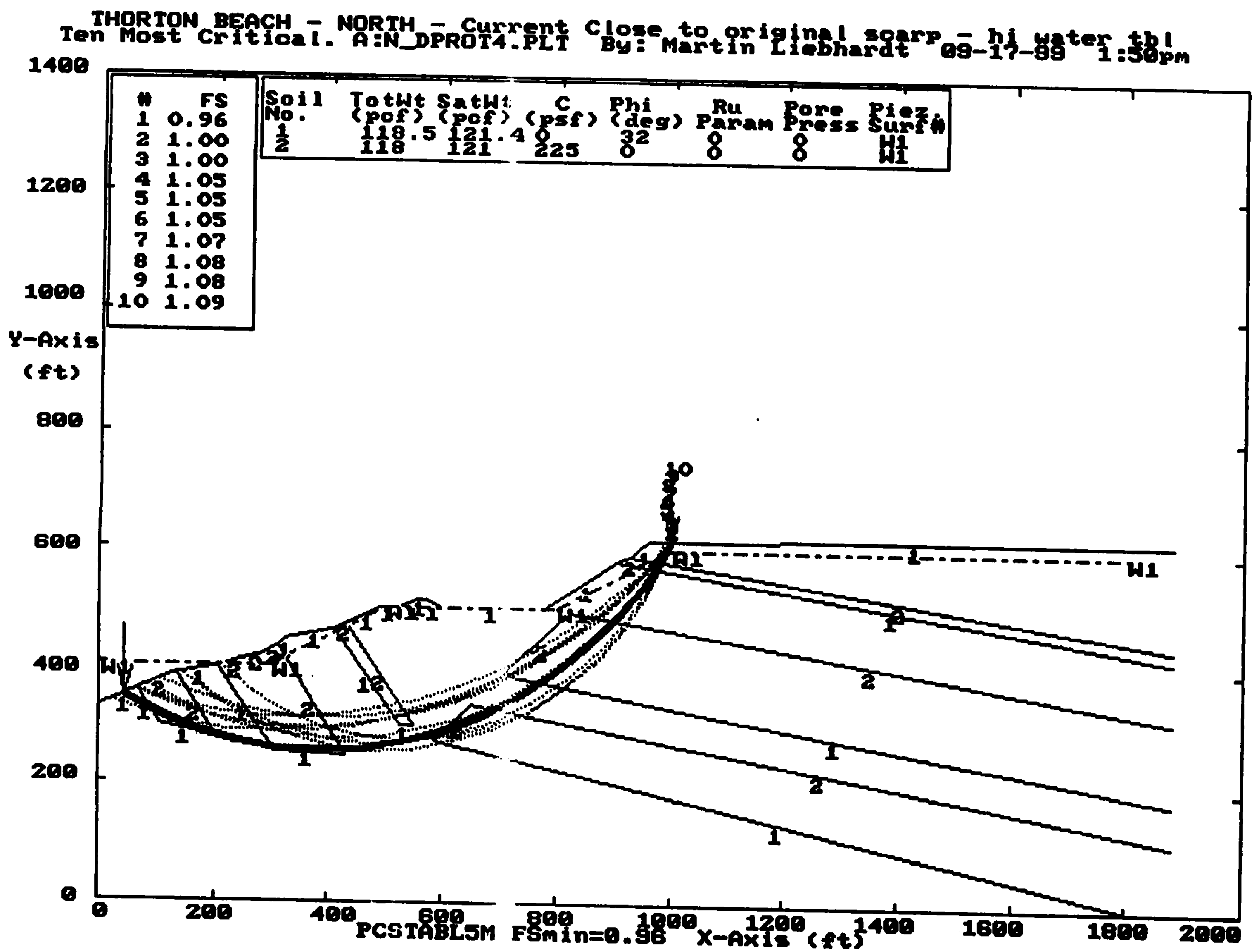


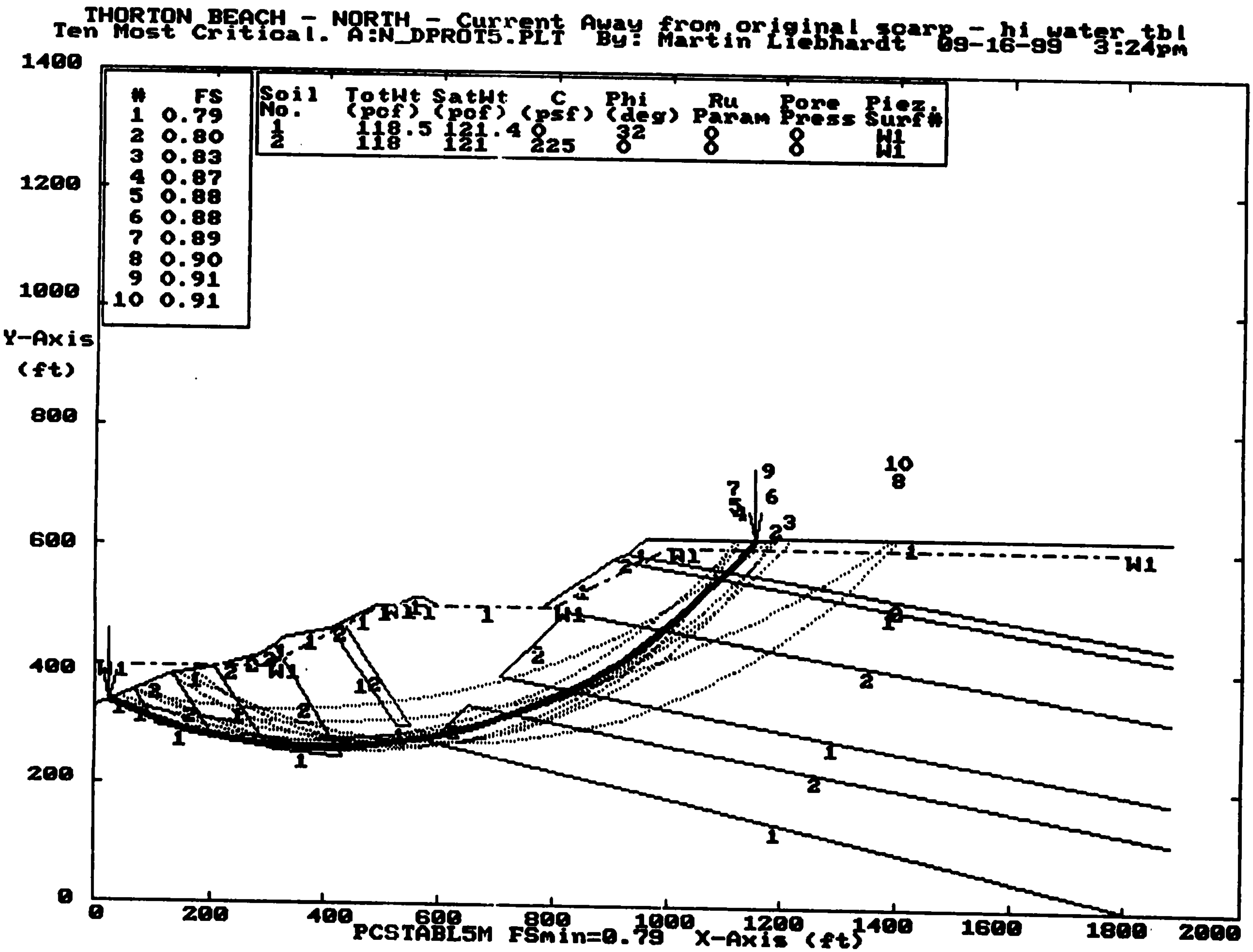
rmations Q – S as mapped by
).

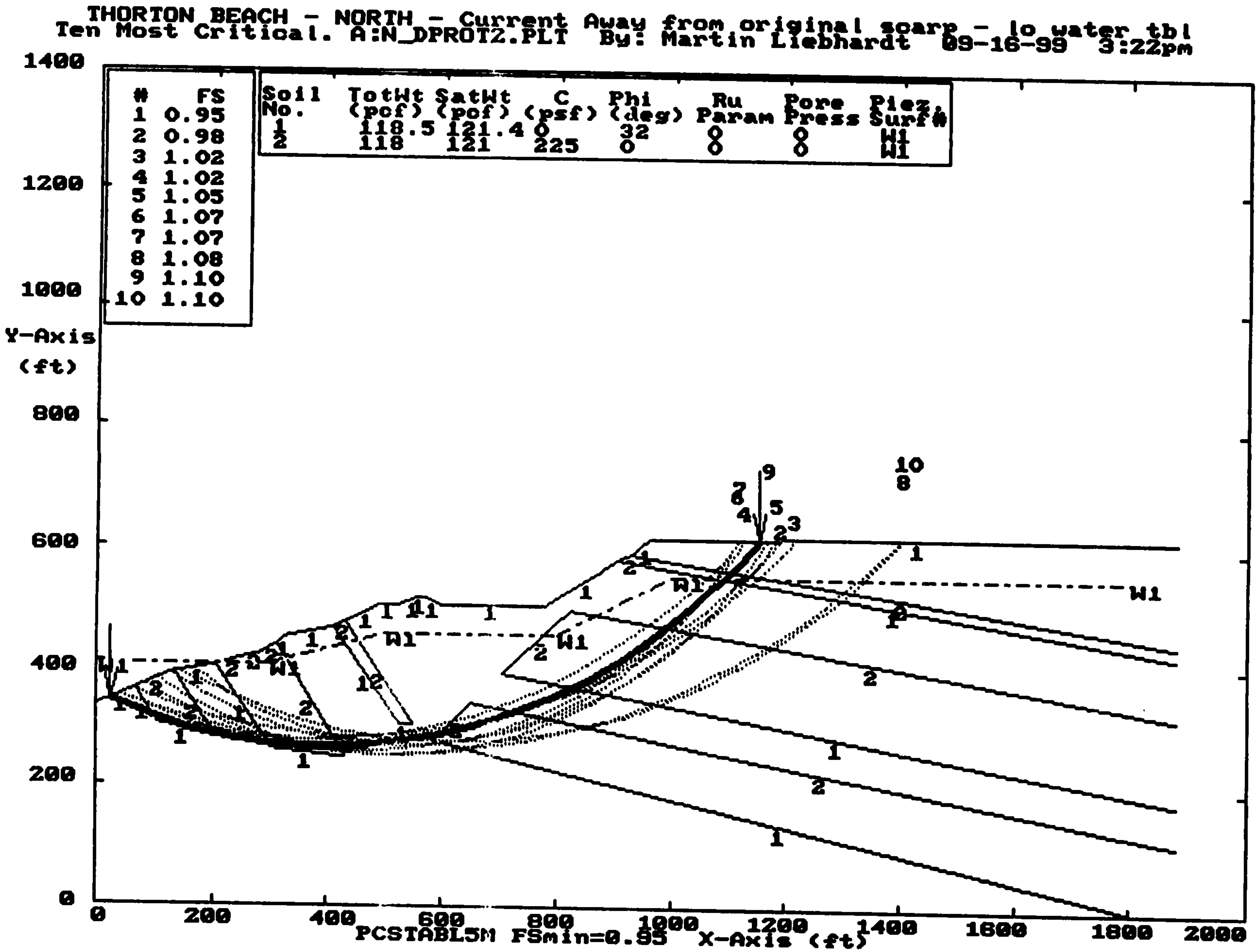
Sand units

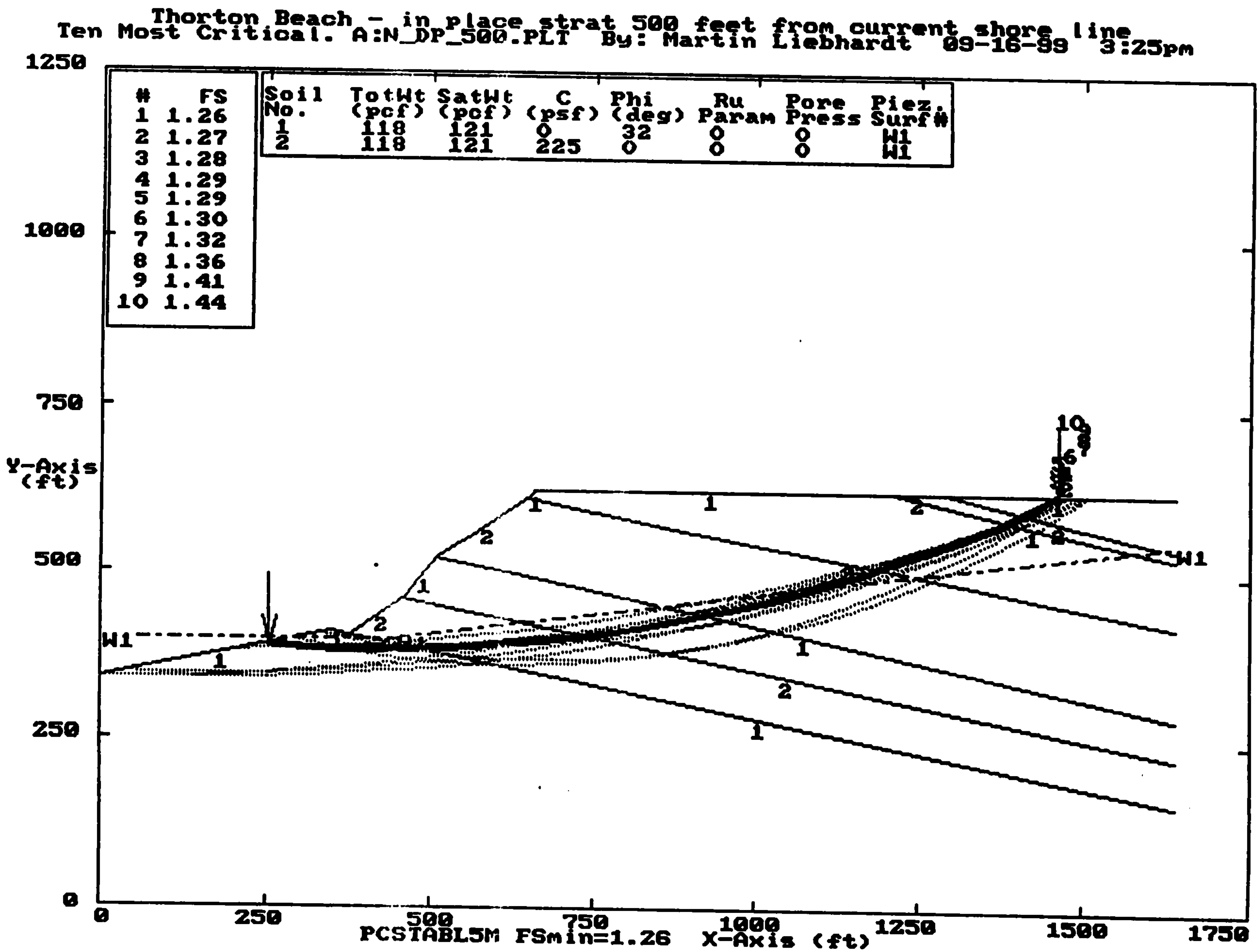
- Quaternary Alluvium

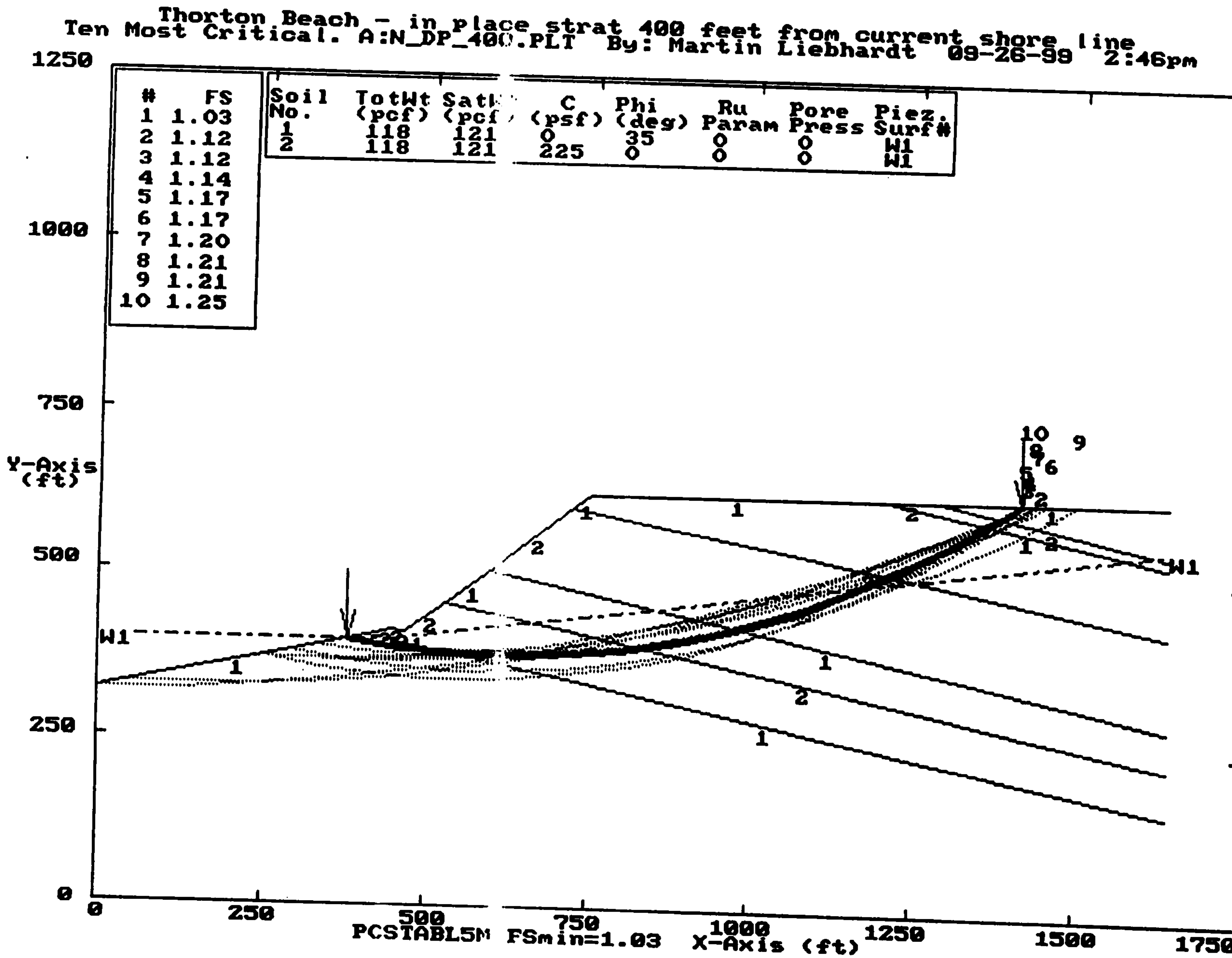
APPENDIX F
Factor of Safety – Computer Modeling
STABL5M Output

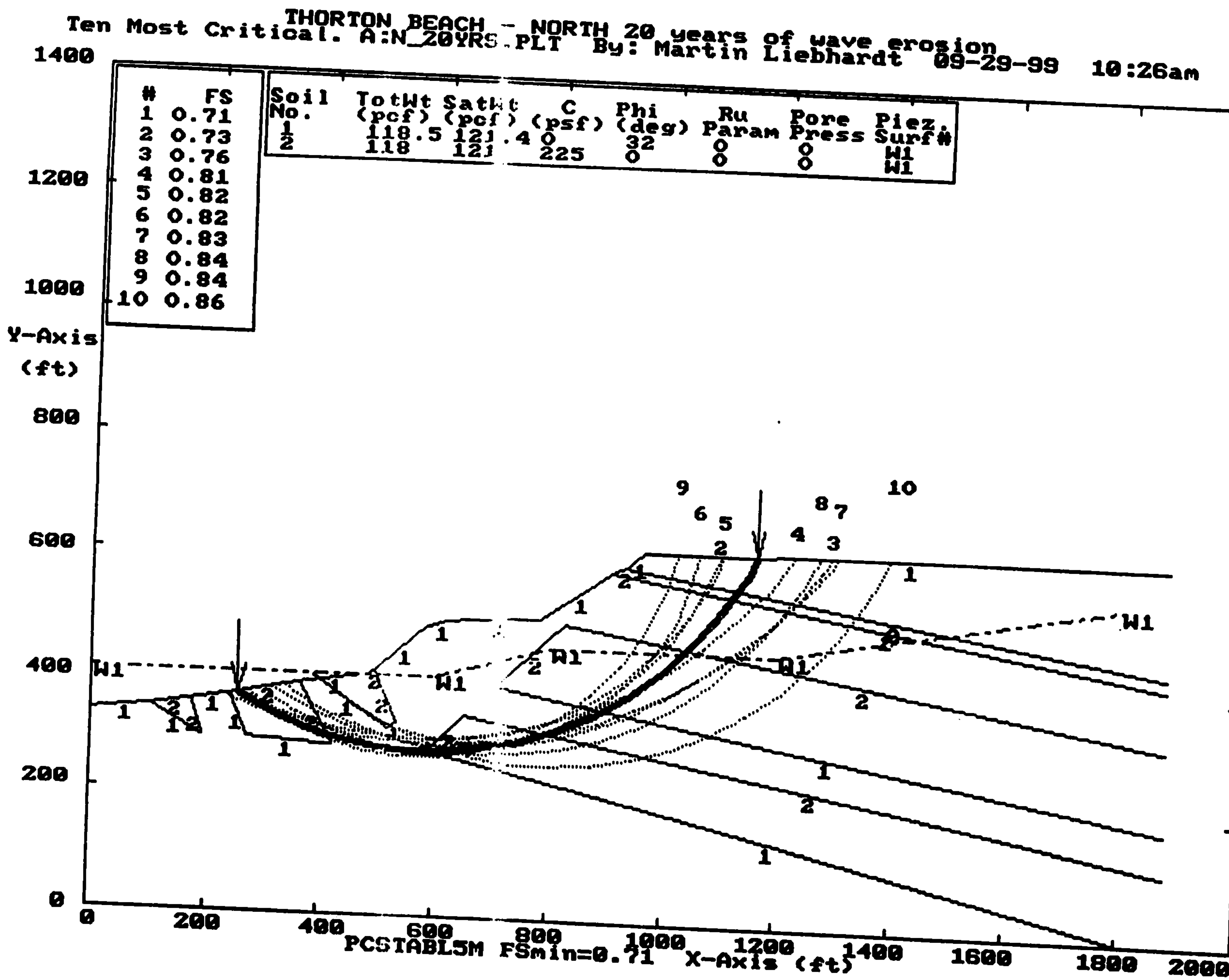

THORTON BEACH - NORTH - Current Close to original scarp - hi water tbl
Ten Most Critical. A:N_DPROT4.PLT By: Martin Liebhardt 08-17-89 1:50pm
FS
1 0.96
2 1.00
3 1.00
4 1.05
5 1.05
6 1.05
7 1.07
8 1.08
9 1.08
10 1.09
Soil No. | TotWt (pcf) | SatWt (pcf) | C (psf) | Phi (deg) | Ru Param | Pore Press | Piez. Surf#
1 | 118.5 | 121.4 | 0 | 32 | 0 | 0 | W1
2 | 118 | 121 | 225 | 0 | 0 | 0 | W1
Y-Axis (ft)
X-Axis (ft)
PCSTABL5M FSmin=0.96
W1
0
200
400
600
800
1000
1200
1400
1600
1800
2000

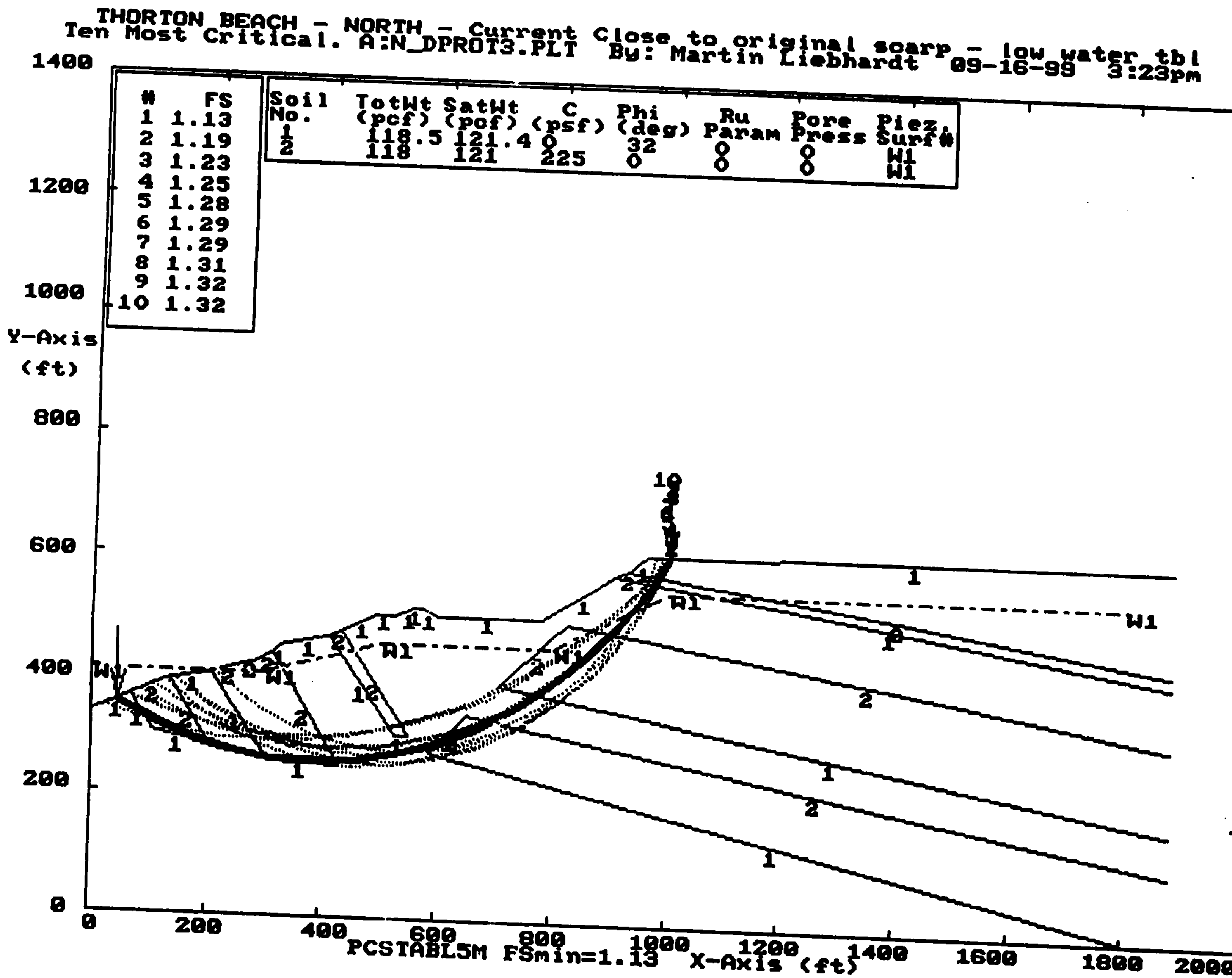

THORTON BEACH - NORTH - Current Away from original scarp - hi water tbl
Ten Most Critical. A:N_DPROT5.PLT By: Martin Liebhardt 09-16-99 3:24pm
FS
1 0.79
2 0.80
3 0.83
4 0.87
5 0.88
6 0.88
7 0.89
8 0.90
9 0.91
10 0.91
Soil No. TotWt (pcf) SatWt (pcf) C (psf) Phi (deg) Ru Param Pore Press Piez. Surf#
1 118.5 121.4 0 32 0 0 W1
2 118 121 225 0 0 0 W1
Y-Axis (ft)
PCSTABL5M FSmin=0.79 X-Axis (ft)


THORTON BEACH - NORTH - Current Away from original scarp - lo water tbl
Ten Most Critical. A:N_DPROT2.PLT By: Martin Liebhardt 09-16-99 3:22pm
FS
1 0.95
2 0.98
3 1.02
4 1.02
5 1.05
6 1.07
7 1.07
8 1.08
9 1.10
10 1.10
Soil No. | TotWt (pcf) | SatWt (pcf) | C (psf) | Phi (deg) | Ru Param | Pore Press | Piez. Surf#
1 | 118.5 | 121.4 | 0 | 32 | 0 | 0 | W1
2 | 118 | 121 | 225 | 0 | 0 | 0 | W1
Y-Axis (ft)
X-Axis (ft)
PCSTABL5M FSmin=0.95
0
200
400
600
800
1000
1200
1400
1600
1800
2000
W1


Thorton Beach - in place strat 500 feet from current shore line
Ten Most Critical. A:N_DP_500.PLT By: Martin Liebhardt 09-16-99 3:25pm
FS
1 1.26
2 1.27
3 1.28
4 1.29
5 1.29
6 1.30
7 1.32
8 1.36
9 1.41
10 1.44
Soil No. | TotWt (pcf) | SatWt (pcf) | C (psf) | Phi (deg) | Ru Param | Pore Press | Piez. Surf#
1 | 118 | 121 | 0 | 32 | 0 | 0 | W1
2 | 118 | 121 | 225 | 0 | 0 | 0 | W1
Y-Axis (ft)
X-Axis (ft)
PCSTABL5M FSmin=1.26
W1


Thorton Beach - in place strat 400 feet from current shore line
Ten Most Critical. A:N_DP_400.PLT By: Martin Liebhardt 09-26-99 2:46pm
FS
1 1.03
2 1.12
3 1.12
4 1.14
5 1.17
6 1.17
7 1.20
8 1.21
9 1.21
10 1.25
Soil No. | TotWt (pcf) | Sat (pcf) | C (psf) | Phi (deg) | Ru Param | Pore Press | Piez. Surf#
1 | 118 | 121 | 0 | 35 | 0 | 0 | W1
2 | 118 | 121 | 225 | 0 | 0 | 0 | W1
Y-Axis (ft)
X-Axis (ft)
PCSTABL5M FSmin=1.03
W1
0
250
500
750
1000
1250
1500
1750


THORTON BEACH - NORTH 20 years of wave erosion
Ten Most Critical. A:N_20YRS.PLT By: Martin Liebhardt 09-29-99 10:26am
FS
1 0.71
2 0.73
3 0.76
4 0.81
5 0.82
6 0.82
7 0.83
8 0.84
9 0.84
10 0.86
Soil No. | TotWt (pcf) | SatWt (pcf) | C (psf) | Phi (deg) | Ru Param | Pore Press | Piez. Surf#
1 | 118.5 | 121.4 | 0 | 32 | 0 | 0 | W1
2 | 118 | 121 | 225 | 0 | 0 | 0 | W1
Y-Axis (ft)
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
PCSTABL5M FSmin=0.71 X-Axis (ft)
W1


THORTON BEACH - NORTH - Current Close to original scarp - low water tbl
Ten Most Critical. A:N_DPROT3.PLT By: Martin Liebhardt 09-16-99 3:23pm
FS
1 1.13
2 1.19
3 1.23
4 1.25
5 1.28
6 1.29
7 1.29
8 1.31
9 1.32
10 1.32
Soil No. TotWt (pcf) SatWt (pcf) C (psf) Phi (deg) Ru Param Pore Press Piez. Surf#
1 118.5 121.4 0 32 0 0 W1
2 118 121 225 0 0 0 W1
Y-Axis (ft)
PCSTABL5M FSmin=1.13 X-Axis (ft)
W1